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AIR FORCE RESEARCH LABORATORY

WC/C-130J Human Vibration Investigation

Suzanne D. Smith

January 2002

Interim Report for February 2001 to September 2001

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Human Effectiveness Directorate
Crew Systems Interface Division
2610 Seventh Street
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14. ABSTRACT
A study was conducted to characterize and assess human vibration in the propeller-driven WC-130J Weatherbird and C-130 Slick aircraft. Accelerations were measured at several sites for the Aerial Weather Reconnaissance Officer (ARWO) station (WC-130J), and at passenger sites located in the vicinity of the propeller plane (C-130J). Cockpit vibrations (copilot seat and lower bunk) were measured in both aircraft. Peak accelerations primarily occurred in the 16-Hz and 100-Hz one-third octave frequency bands at all sites and in all three orthogonal directions. These vibrations were associated with the aircraft rotor speed (17 Hz) and blade passage frequency (102 Hz), respectively. None of the seat pan accelerations exceeded the 16-Hr Fatigue-Decreased Proficiency Boundary of the ANSI S3.18-1979 exposure standard (limited to 1 – 80 Hz). The results showed that synchrophaser function had no effect on the measured accelerations. However, there was a substantial reduction in the 16-Hz one-third octave accelerations associated with dynamic balancing of the propellers. It was recommended that mitigation strategies include routine balancing of the propellers and further investigation of synchrophaser function. New target vibration levels will be required for the cargo area given the limitation of existing exposure criteria for predicting human vibration sensitivity in propeller-driven aircraft.

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PREFACE

This report describes the study conducted by the Air Force Research Laboratory, Human Effectiveness Directorate (AFRL/HECB) (Wright-Patterson AFB, OH) to document and evaluate the human vibrations aboard the WC-130J/C-130J aircraft at the request of Aeronautical System Center, C-130 Development System Office (ASC/GRB). The study was performed in accordance with the WC-130J Human and Equipment Vibration Environment Investigation (amendment to WC-130J QT&E Test Plan, TIS 99066). Specifically, AFRL/HECB focused their effort on characterizing and assessing the vibration at the Aerial Reconnaissance Weather Officer (ARWO) station in the WC-130J (Weatherbird) aircraft, and at the center and left (port) side passengers located in the vicinity of the propeller plane in the C-130J (Slick) aircraft. In both aircraft, cockpit vibrations at the copilot and lower bunk were also collected and evaluated by AFRL/HECB. Data were collected during four separate flights commencing on 10 February 2001 and ending on 16 February 2001. This study was partially funded by ASC/GR. The primary POC for the study was Mr. William Slusher, ASC/GRB. The ARFL/HECB principal investigator was Dr. Suzanne D. Smith. The Air Force Reserve Command (AFRC) provided the C-130 derivative aircraft (Tail Number AF S/N 98-5307) for this study. The 53rd WRS, AFRC, Keesler AFB, MS provided the copilot, Dropsonde Operator (DSO) and Aerial Reconnaissance Weather Officer (ARWO). The AFFTC 412 TW provided the test pilot, test conductor, and additional personnel. AFIERA/RSHI (Brooks AFB, TX) measured vibration at the Dropsonde Operator (DSO) station and Lockheed Martin Aerospace (LM Aero) (Marietta, GA) measured equipment vibration at various locations in the aircraft. The 418th FLTS (Edwards AFB, CA) collected noise data during the study. Their findings are reported under separate documentation. This is the final report for this study and includes the information provided in the preliminary report entitled WC/C-130J Human Vibration Investigation, AFRL/HECB, dated 3 April 2001. The author acknowledges the assistance of Mr. Raymond J. Newman and Ms. Jeanne A. Smith (Veridian Engineering), and 1Lt Charles M. Loyer in setting up the equipment and instrumentation and performing data reduction and documentation at Wright-Patterson AFB, OH.

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WC/C-130J HUMAN VIBRATION INVESTIGATION

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INTRODUCTION

Purpose

The purpose of this investigation was to conduct human vibration evaluations aboard the WC-130J/C-130J. At the request of Air Systems Command (ASC/GRB), the Air Force Research Laboratory, Human Effectiveness Directorate (AFRL/HECB) agreed to participate in the team effort to document and evaluate human and equipment vibration in accordance with the WC-130J Human and Equipment Vibration Environment Investigation (amendment to WC-130J QT&E Test Plan, TIS 99066). AFRL/HECB specifically focused on characterizing the vibration at the Aerial Reconnaissance Weather Officer (ARWO) station and in the cockpit. AFIERA/RSHI measured vibration at the Dropsonde Operator (DSO) station and Lockheed Martin Aerospace (LM Aero) measured equipment vibration at various locations in the aircraft. In addition, human vibration data were collected in the C-130J (Slick) aircraft with the ARWO and DSO pallets removed and passenger seats installed along the propeller plane. The 418th FLTS collected noise data during the study. This report describes the AFRL results at the ARWO station and cockpit stations for the WC-130J aircraft, and at the center and side passenger seat locations for the C-130J (Slick) aircraft.

Background

The study was conducted in response to recommendations made by AFIERA/RSHI (Consultative Letter, AFIERA-RS-BR-CL-2000-0086) for a more thorough evaluation of the human and equipment vibration aboard the Weatherbird (WC-130J). In August 2000, AFIERA conducted a survey of vibration at the DSO station and found that the measured levels exceeded the 16-hr Fatigue-Decreased Proficiency Boundary and, in some cases, the Exposure Limit of the American National Standards Institute ANSI S3.18-1979 entitled "Guide for the Evaluation of Human Exposure to Whole-Body Vibration" (1). In several instances, the levels exceeded the limits set for lower-duration exposures. The associated frequency bands included low frequency (below 10 Hz) and the 16-Hz one-third octave frequency band. The latter vibration coincided with the 17-Hz rotor speed. The survey was prompted by Deficiency Reports (CAT 1 DR #FB2805000286 and CAT 2 DR #FA9107000029), which described very uncomfortable and even intolerable vibration generated at various times during flight and centered in the propeller plane where the DSO and ARWO stations are located. A perceptible jitter in the displays at both the DSO and ARWO pallets was also reported with this vibration. The levels of vibration were fatiguing to the occupants. The current Test Plan includes a rigorous measurement regime to assess possible contributing factors, including the evaluation of several aircraft configurations and flight test conditions.

METHODS AND MATERIALS

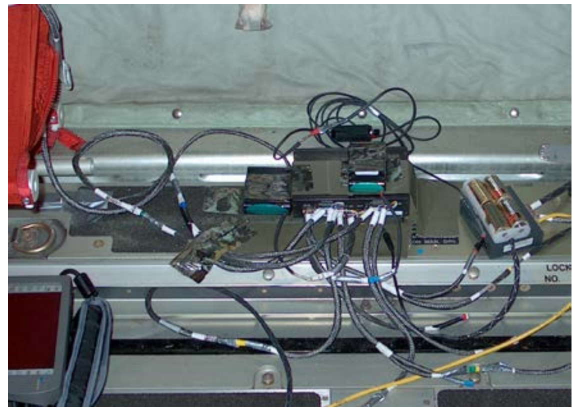
Aircraft Equipment and Flight Crew

AFRC provided WC-130J Tail Number AF S/N 98-5307 for conducting this study. Crew personnel were provided by the AFFTC 412 TW (test pilot, test conductor) and the 53rd WRS, AFRC, Keesler AFB, MS (Copilot, DSO, ARWO). The ARWO and DSO pallets were removed and selected passenger seats installed in the propeller plane to obtain the C-130J (Slick) setup.

Vibration Measurement Equipment

Two Remote Vibration Environment Recorders (REVERs) were used to collect the acceleration data at specified locations. Figure 1a shows the location of the first recorder mounted to the seat platform in back of the ARWO seat (Weatherbird aircraft). This recorder collected all ARWO station data. The second recorder was secured underneath the lower bunk located in the cockpit and was used to collect both bunk and copilot data. For the C-130J (Slick) aircraft, the first recorder was mounted next to the left (port) side passenger seat as shown in Figure 1b. The second recorder remained in the cockpit for collecting bunk and copilot data.

a. WC-130J (Weatherbird)



b. C-130J (Slick)

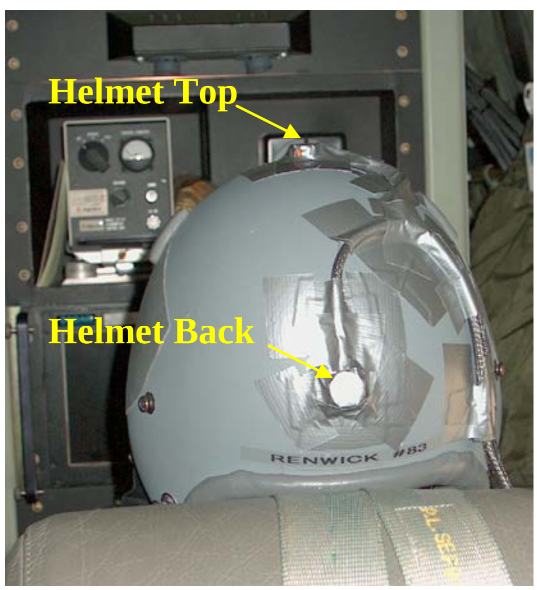
Figure 1 DAU Locations in WC/C-130J Aircraft

Each 16-channel data acquisition unit (DAU) measured approximately 16.5 cm x 10 cm x 4 cm. The DAU enclosure was fabricated using Delrin and T6-6061 aluminum and provided EMI (electromagnetic interference) shielding. Two types of battery packs were available for use depending on the flight time. The first was rated at 12 volts/2.1 amp-hours and measured approximately 5 cm x 9 cm x 3 cm. The battery operated for up to two hours. The second was rated at 12 volts/3.5 amp-hours and measured approximately 7 cm x 9 cm x 3 cm. This battery operated for up to 3.5 hours. Two battery packs were connected to each DAU to extend the operation time. The total system weighed 1.4 kg - 1.6 kg (3.0 – 3.5 lbs) depending on the battery selection. Triaxial accelerometer packs and pads were attached to selected sites for measuring accelerations in the fore-and-aft (X), lateral (Y), and vertical (Z) directions as listed in Measurement Sites and Directions and shown in Figures 2a - g. Each accelerometer pack measured 1.9 cm in diameter and 0.86 cm in thickness and weighed approximately 5 gm (25 gm with connecting cable) (Figures 2a, 2c, 2d, 2f, 2g.) Triaxial seat pads were used for measuring the vibration transmitted to the occupant via the seat pan and seat back in accordance with the ANSI S3.18-1979 (1) (also International Standards Organization “Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration – Part I: General

Requirements (ISO 2631-1: 1997) (2)) (Figures 2b, 2e, 2f, 2g.) The pad consisted of a flat rubber disk approximately 20 cm in diameter and weighing 355 gm (with connecting cable).

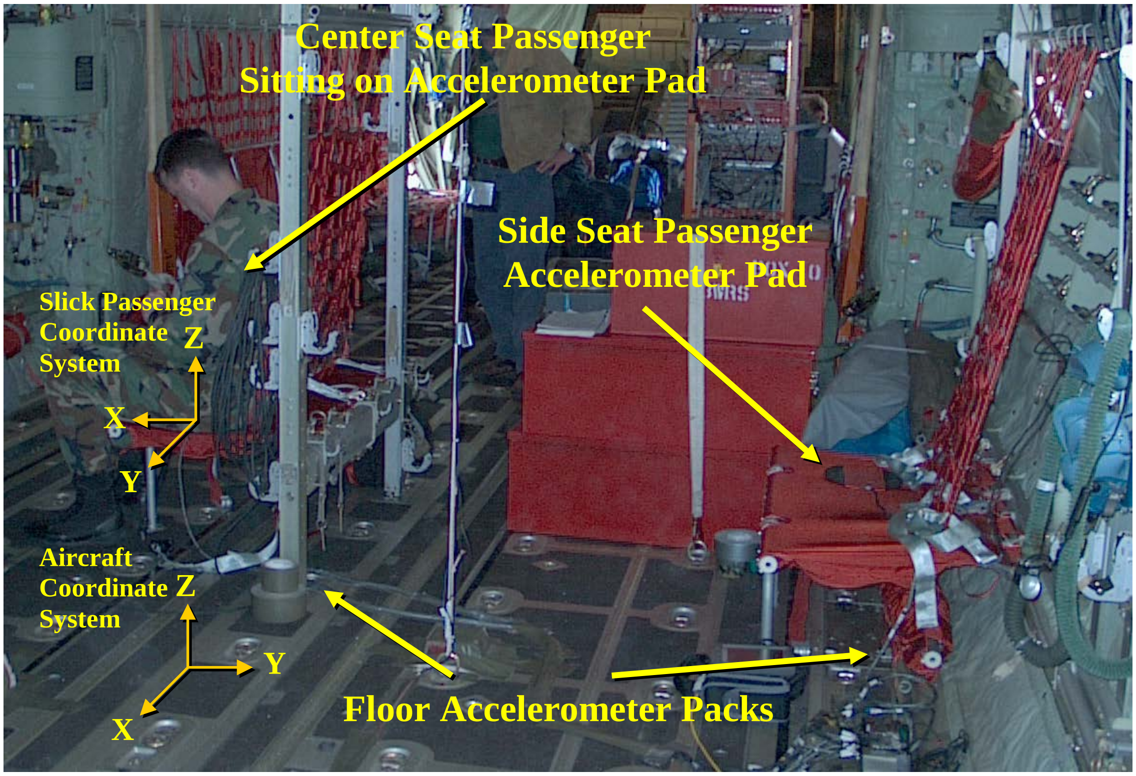
a. ARWO Seat Base Accelerometer Pack

b. ARWO Seat Pan and Seat Back Accelereometer Pads



c. ARWO Helmet Top and Helmet Back Accelerometer Packs

Figure 2 Measurement Equipment and Sites



d. Passenger Center and Side Seat Pan Accelerometer Pads and Floor Accelerometer Packs

e. Copilot Seat Base Accelerometer Pack
(located on lower front seat cross-beam)

f. Copilot Seat Pan Accelerometer Pad

Figure 2 Measurement Equipment and Sites (Continued)

g. Lower Bunk Accelerometer Locations

Figure 2 Measurement Equipment and Sites (Continued)

Embedded in the disk was a triaxial accelerometer pack. Cable connections between the accelerometers and DAU were made via break-away connectors (when necessary) that required less than 21.8 N (4.9 lbs) to separate. The two REVERs were daisy-linked via cable to provide simultaneous data collection at all selected sites. The DAU, battery packs, cables, accelerometers, seat pads, and other auxiliary equipment were secured using heavy duty mounting tape and/or duct tape. A triggering device, measuring 7.6 cm in length and 2.2 cm in diameter with a weight of 20 gm, was used by the AFRL investigator to initiate simultaneous data collection from the two connected recorders (ARWO station and cockpit in WC-130J; center and left passenger and cockpit in C-130J.)

Measurement Sites and Directions

WC-130J ARWO Station

ARWO seat base (fore-and-aft (X), lateral (Y), and vertical (Z) using one triaxial accelerometer pack) (Figure 2a).

ARWO seat pan (fore-and-aft (X), lateral (Y), and vertical (Z) using one triaxial accelerometer pad) (Figure 2b).

ARWO display (vertical (Z) using triaxial accelerometer pack – one channel) ARWO seat back (fore-and-aft (X), lateral (Y), and vertical (Z) using one triaxial accelerometer pad) (Figure 2b).

ARWO Helmet Top (fore-and-aft (X), lateral (Y), and vertical (Z) using one triaxial accelerometer pack) (Figure 2c).

ARWO helmet back (fore-and-aft (X), lateral (Y), and vertical (Z) using one triaxial accelerometer pack) (Figure 2c).

C-130J Passengers

Passenger center and left side seat floors (floor area beneath or near seats) (fore-and-aft (X), lateral (Y), and vertical (Z) using one triaxial accelerometer pack at each floor location) (Figure 2d).

Passenger center and left side seat pans (fore-and-aft (X), lateral (Y), and vertical (Z) using one triaxial accelerometer pad at each seat location) (Figure 2d).

WC/C-130J Cockpit

Copilot seat base (fore-and-aft (X), lateral (Y), and vertical (Z) using one triaxial accelerometer pack) (Figure 2e).

Copilot seat pan (fore-and-aft (X), lateral (Y), and vertical (Z) using one triaxial accelerometer pad) (Figure 2f).

Lower bunk seat base (fore-and-aft (X), lateral (Y), and vertical (Z) using one triaxial accelerometer pack) (Figure 2g).

Lower bunk seat pan (fore-and-aft (X), lateral (Y), and vertical (Z) using one triaxial accelerometer pad) (Figure 2g).

Note: All measurements were relative to the human body coordinate system. In the WC-130J (Weatherbird), the ARWO coordinate system coincided with the aircraft coordinate system as shown in Figure 2d. In the C-130J (Slick) aircraft, the occupants sat sideways. Fore-and-aft human body and floor measurements corresponded to the lateral direction in the aircraft; lateral human body and floor measurements corresponded to the fore-and-aft direction in the aircraft as shown in Figure 2d.

Data Collection and Processing Scheme

Data were collected for selected combinations of aircraft configurations and flight test conditions with the intent of identifying contributing or causal factors that may have influenced the vibration.

WC-130J Aircraft Configurations

Heavy weight (64500-68000 kg or 140-150K lbs) vs. light weight aircraft (49900-54400 kg or 110-120K lbs) (propeller balance as-is).

Synchrophaser off vs. synchrophaser on.

Propeller balance as-is vs. dynamically balanced propellers.

With external tanks vs. external tanks removed (props balanced).

C-130J Aircraft Configurations

Synchrophaser off vs. synchrophaser on.

Note: (C-130J configuration was light weight, props balanced, pallets and tanks removed for all data collection).

WC/C-130J Flight Test Conditions

Altitude (4K, 10K, 18K, 24K, and 30K feet PA).

(Note: All altitudes are reported in feet PA (Pressure Altitude)).

Airspeed (140 KIAS (Knots in Airspeed) (4K feet only), 180 KIAS, 220 KIAS, MCP (Maximum Continuous Power)).

Throttle setting (10K and 24K feet only) (inboard propellers to idle, inboard propellers to MCP, outboard propellers to idle, outboard propellers to MCP, all propellers to idle, all propellers to MCP, all propellers retarded for constant speed dive).

The specific combination of an aircraft configuration and flight test condition defined a test point. The triggering device was set up to collect data for 30 seconds at each test point. Data collection was initiated upon prompting by the Test Conductor. The data were filtered at 250 Hz (anti-aliasing) and sampled at 1024 samples per second. The resultant acceleration time histories were processed using one-third octave band frequency analysis in accordance with ANSI S3.18-1979. Constant bandwidth analysis was also done in 0.5 Hz increments using standard signal processing techniques.

RESULTS

Data Repeatability

All figures referenced in the RESULTS are located in APPENDIX C. The combinations of aircraft configurations and flight test conditions provided for an extensive database for assessing human vibration and possible factors influencing the vibration. However, given restrictions of aircraft availability and time constraints, none of the data points were repeated during the formal data collection period. In order to assess the repeatability of the acceleration data, ten 30-second segments were collected at the ARWO station over a 30-minute period during the flight from Dobbins AFB in Atlanta to Keesler AFB in Mississippi at a constant altitude and airspeed. This period was comparable to the amount of time required to collect data for all flight conditions (altitude, airspeed, and power setting) for a particular aircraft configuration. During this period, the aircraft was heavy with props as-is and the synchrophaser in the off position. Figure C-1 illustrates the one-third octave and constant bandwidth rms acceleration responses at the ARWO seat pan. The figure shows distinct peaks associated with the 17 Hz rotor speed (16-Hz one-third octave band) and 102 Hz blade passage frequency (100-Hz one-third octave band) in all directions. There were minimal variations in the responses over the 30-minute period.

Variations observed below 10 Hz were attributed to intermittent buffeting or movement by the occupant who was unaware of the data collection. The results for the 30-minute period strongly suggested that variations observed during formal data collection reflected the effects of the specific aircraft configuration and flight test condition.

WC-130J ARWO Station

WC-130J ARWO - Frequency Response and Exposure Assessment

Representative frequency response profiles at the ARWO seat base, seat pan, and seat back (X, Y, and Z directions) at 24000 feet PA are shown in Figures C-2 – C-4, respectively. The figures include the results for all tested throttle settings at 24000 feet PA. (Throttle setting data were grouped together – see Effects of Aircraft Configurations/Flight Test Conditions on ARWO Seat Vibration.) Also included are the 8-hr, 16-hr, and 24-hr Fatigue-Decreased Proficiency Boundaries (1). Representative frequency response profiles for the helmet top (X, Y, and Z directions) and helmet pitch at 24000 feet PA are shown in Figures C-5 and C-6, respectively. The ANSI (1) boundaries are not shown since these measurement sites are not included as part of the ANSI (1) assessment process. No acceleration levels measured at the ARWO seat pan exceeded the ANSI S3.18-1979 16-hr Fatigue-Decreased Proficiency Boundaries (1) in any direction for any aircraft configuration and flight test condition between 1 and 80 Hz. The one-third octave analysis did show that peak responses at the ARWO seat, helmet, and display occurred in the 16-Hz one-third octave frequency band and the 100-Hz one-third octave frequency band, regardless of the direction of measurement, as previously shown in Figure C-1. There were instances where the 16-Hz peak was not easily observed, as shown in Figure C-2 (Seat Base X) and Figure C-4 (Helmet Top X). As described previously, the 16-Hz and 100-Hz peaks were specifically associated with the rotor speed (17 Hz) and blade passage frequency (102 Hz), respectively. Table B-1 includes the synchrophaser on data for the props as-is and balanced props configurations for comparison to the respective limits. While the vertical (Z-axis) acceleration exposure boundary is 0.383 m/s^2 rms in the 16-Hz band, the highest measured vertical acceleration levels at the seat pan (for the constant altitude and airspeed conditions) reached 0.328 m/s^2 rms at an altitude of 4000 feet PA and 220 KIAS. However, the seat base vertical acceleration did exceed the limit at 0.424 m/s^2 rms in the 16-Hz band at 4000 feet PA and 180 KIAS. It is emphasized that the seat pan acceleration data is required for assessing the exposure in accordance with the ANSI standard since the measurement represents the vibration entering the occupant and takes into account any damping (or increase) of the motion associated with the seating system. It is also emphasized that the 100-Hz frequency band is not included in the ANSI exposure criteria (1).

The vertical display accelerations were below 0.620 m/s^2 rms for the light-weight aircraft, synchrophaser on, props as-is configuration, and below 0.300 m/s^2 rms for the light-weight aircraft, synchrophaser on, props balanced configuration between 1 and 80 Hz. These values are well below the 1 to 4 Hz limits for controls and displays given in Section 5.8.4.2, Figure 42 of the MIL-STD-1472C (1984) (3). In Figure 42, the limit is about 2.5 m/s^2 rms at 1.0 Hz increasing to about 10 m/s^2 rms at 4 Hz. (The current MIL-STD-1472F (1999) does not include this figure.)

Vibration occurring below 10 Hz was difficult to assess relative to the various configurations and conditions of the study due to the influence of turbulence and aircraft buffeting. While occurring periodically, such environmental conditions were associated with increased vibration levels below 10 Hz during level flight. Higher magnitude low frequency vibration was associated with the throttle setting test conditions where the aircraft was changing airspeed or changing altitude during data collection. As shown in Figures C-2, C-3, and C-4, these levels did not exceed the 16-Hz Fatigue-Decreased Proficiency Boundary (1) at the ARWO seat. There did tend to be higher helmet accelerations as compared to the seat accelerations below 10 Hz. (The results above 10 Hz are described later). This was most likely due to the greater transmission of motion expected at the head at lower frequencies associated with the major human body sensitivities (1 to 2 Hz in X and Y, and 4 to 8 Hz in Z). In some instances, the higher motions may have been due to small voluntary head movements.

Crew members located in the propeller plane commented that the vibrations felt during these test flights were not the worst they had encountered but were still quite annoying and thought to contribute to fatigue during long flights. Terms such as "buzzing" and "tingling" were used to describe the sensations. These terms are consistent with the sensations described in human vibration studies conducted at AFRL for frequencies above 10 Hz. As a consequence of these findings, AFRL confirmed that vibration around 100 Hz at levels comparable to those experienced during flight could be felt by the seated occupant. The relative contribution of the 100-Hz vibration to the annoyance reported by crew members was unknown.

Given the association between the distinct peaks observed in the human vibration responses and the dynamic characteristics of the propulsion system, the analysis was focused on assessing the peak vibration levels observed in the 16-Hz and 100-Hz one-third octave bands. Figure C-7 illustrates the ARWO seat responses in these frequency bands for the light-weight aircraft with the synchrophaser on at each altitude and airspeed at level flight (180, 220, and MCP KIAS). Included are the props as-is and props balanced data. Figure C-8 includes the ARWO mean seat responses at each seat measurement site and direction for the props as-is and props balanced conditions. There were differences observed in the responses relative to the measurement site, measurement direction, and frequency band. Figures C-7 and C-8 show that, in the 16-Hz third-octave band, the lowest seat vibration occurred in the fore-and-aft (X) direction regardless of the seat measurement site. Of particular interest was the high lateral (Y) seat back accelerations for the props as-is configuration. The accelerations reduced to levels which were more similar to those occurring at the seat base and seat pan once the props were balanced (Figure C-8b). In the 100-Hz third-octave band, the seat back fore-and-aft (X) accelerations were notably lower than at the seat base and seat pan (Figures C-7 and C-8a), while the seat back vertical (Z) accelerations tended to be higher than the seat base and seat pan (Figures C-7 and C-8c). Noteworthy was the higher accelerations occurring at the seat base and seat back as compared to the seat pan in the vertical direction (Fig. B-8c).

Figure C-8 includes the mean ARWO helmet translational responses. Figure C-9 shows the mean ARWO helmet pitch responses in the 16-Hz and 100-Hz frequency bands. The helmet translational responses tended to be lower as compared to the ARWO seat responses, particularly in the 100-Hz frequency band and depending on the particular seat measurement site and direction. Figure C-9 depicts very low helmet pitch. At the helmet back, the 16-Hz lateral (Y) motions for the props as-is configuration tended to be noticeably smaller than in the other axes and as compared to the helmet top Y, suggesting some helmet roll and/or yaw rotations. While these rotations could not be calculated from the available data, they were assumed to be quite low.

Figure C-8c includes the display vertical vibration and shows that the display vibration tended to be higher than at the seat pan, seat base, or helmet (top and back) at 16 Hz. The display and seat base vibrations were similar in the 100-Hz band, and, consequently, higher than the seat pan vibrations. With regard to the ARWO display vibration, the reports of jitter by both the co-pilot and ARWO may have been due to problems with the image display electronics and not necessarily due to vibration. During the testing period, there were no reports of visual blurring. Visual blurring has been observed experimentally at higher frequencies. It is cautioned that the display vibration in the horizontal plane was unknown. A review of the LM Aero data suggested that there was relatively high lateral motion in the ARWO rack that houses the display in the 16-Hz frequency band (props as-is).

WC-130J ARWO - Effects of Aircraft Configurations/Flight Test Conditions

The following summarizes the observations made in the 16-Hz and 100-Hz frequency band responses relative to the aircraft configurations and flight test conditions set forth in the Measures of Performance (MOPs) of the Test Plan.

Aircraft Weight (WC-130J ARWO). As shown in the mean data depicted in Figure C-10, higher accelerations were observed in the 16-Hz band vertical vibration for the light aircraft as compared to the heavy aircraft.

Synchrophaser Function (WC-130J ARWO). There appeared to be no influence of synchrophaser function on the measured accelerations. While certain conditions showed higher accelerations below 10 Hz with the synchrophaser on (particularly at 10K feet PA for the light aircraft), the low frequency vibration coincided with turbulence or buffeting reported during data collection.

Propeller Balance (WC-130J ARWO). Figures C-7, C-8, and C-9 show that the 16-Hz band vibrations at the ARWO seat, helmet, and display were reduced to varying degrees with the props balanced configuration for most vibration directions, aircraft altitudes, and airspeeds. Table B-1 lists the seat pan accelerations in all three directions for the three sustained speeds for the props as-is and props balanced configurations. Also listed are the highest and lowest reductions occurring once the props were dynamically balanced. No obvious effects of prop balancing were observed in the 100-Hz band. Figure C-11 illustrates the effect of balancing the propellers on the frequency response at the seat pan in the lateral (Y) direction. The figure shows the isolated effect in the 16-Hz band. The reductions seen below 10 Hz have not been fully investigated but were not necessarily observed at other altitudes and airspeeds. Again, turbulence or buffeting was shown to affect the low frequency response.

External Tanks Removed (WC-130J). No clear effects were observed with the tanks removed.

Altitude and Airspeed (WC-130J ARWO). There appeared to be some effect of altitude and airspeed on the accelerations occurring at the ARWO station, depending on the aircraft configuration, location, and direction of the measurement. As demonstrated in Figure C-7, the most consistent effect was the coincidence of the lowest accelerations in the 16-Hz band with the higher airspeeds, particularly the airspeed associated with MCP. (In some cases, MCP ~ 250 KIAS.) In contrast, higher accelerations tended to be associated with the higher airspeeds, particularly MCP, in the 100-Hz band. At 100 Hz, higher accelerations also tended to occur at higher altitudes depending on the location and direction of the measurement.

Throttle Setting (WC-130J ARWO). In general, the ARWO seat accelerations associated with selected throttle settings fell within the ranges observed for the constant airspeeds above 10 Hz with no clear effects being observed. As noted previously, higher magnitude low frequency vibration was associated with the throttle setting conditions.

C-130J (Slick) Passengers

C-130J Passengers - Frequency Response and Exposure Assessment

Figure C-12 shows representative frequency response profiles at 24000 feet PA for the C-130J (Slick) configuration (left side passenger seat). As with the Weatherbird, peak responses at both passenger locations coincided with the 17-Hz rotor speed (16-Hz third-octave) and 102-Hz blade passage frequency (100-Hz third-octave). No accelerations exceeded the 16-Hr Fatigue-Decreased Proficiency Boundary between 1 and 80 Hz (1). As shown in Figure C-12 for the left side passenger, the throttle setting conditions showed a tendency for higher low frequency vibration (less than 10 Hz). This was also the case at the center location.

For the C-130J aircraft, only the props balanced configuration was evaluated. Figures C-13 and C-14 illustrate the one-third octave accelerations in the 16-Hz and 100-Hz frequency bands, respectively, for the center passenger and left (port) side passenger seat and floor. The figures include the responses at each altitude and airspeed. Figure C-15 shows the mean accelerations in the 16-Hz and 100-Hz frequency bands. As mentioned previously, the directions of the measurements were relative to the body coordinate system. Therefore, since the passengers were seated sideways relative to the aircraft, the fore-and-aft body direction corresponded to the lateral direction relative to the aircraft coordinate system. Likewise, the lateral body direction corresponded to the fore-and-aft direction of the aircraft.

Figures C-13 and C-15 indicate that the lowest 16-Hz vibration occurred in the lateral (Y) direction at the passenger locations. (This direction corresponded to the fore-and-aft direction of the aircraft where low vibrations were observed at the ARWO station.) The figures also show no substantial differences between the center and side seat pan accelerations in the 16-Hz band for each respective direction. However, at the side floor site, the accelerations tended to be higher in the fore-and-aft and vertical directions, and lower in the lateral direction as compared to the center floor. The greatest differences between the vibrations at the two passenger locations occurred in the 100-Hz frequency band. In the 100-Hz frequency band, the side passenger seat pan showed higher accelerations with exceptionally high fore-and-aft vibration as compared to the center passenger seat pan, particularly in the fore-and-aft (X) direction. These levels were around 2 m/s^2 and above (Figure C-14). The high fore-and-aft side seat pan accelerations were most likely due to the mounting of the seat to the sidewall, where the vibration in the prop plane (lateral direction of the aircraft) was assumed to be high. It should be noted that a relatively light passenger (61.2 kg or 135 lbs) occupied the side passenger seat as compared to the center seat occupant (95.2 kg or 210 lbs). While there may have been some effects of body weight on the seat pan measurement, it was assumed that these effects did not entirely account for the substantial differences observed between the two passenger locations. As also shown in Figures C-14 and C-15, the center passenger horizontal seat pan accelerations were lower as compared to the horizontal floor accelerations. In contrast, the side passenger horizontal seat pan accelerations were higher as compared to the floor horizontal accelerations. Both locations showed higher floor accelerations as compared to the seat pan accelerations in the vertical direction, with notably higher vibration levels observed at the center floor. The center floor levels were about 3 m/s^2 rms and higher (Figure C-14). The higher floor accelerations along the centerline of the aircraft were quite noticeable in the feet of standing passengers. The floor was sectioned, which may have influenced the center floor measurements. It was also speculated that the mounting configuration (using the center poles) might have contributed to the lower vertical seat pan accelerations along the centerline.

<u>C-130J Passengers - Effects of Aircraft Configurations/Flight Test Conditions</u>

The following summarizes the observations made in the 16-Hz and 100-Hz frequency band responses for the C-130J passengers relative to the aircraft configurations and flight test conditions set forth in the Measures of Performance (MOPs) of the Test Plan.

<u>Heavy vs Light Aircraft (C-130J Passengers).</u> Not compared for the C-130J (Slick) configuration.

Synchrophaser Effects (C-130J Passengers). As described for the WC-130J aircraft, there appeared to be no clear influence of synchrophaser function on the vibrations measured in the C-130J aircraft.

Propeller Balance (C-130J Passengers). Not compared for the C-130J (Slick) aircraft. It is emphasized that the data depicted in Figures C-13 through C-15 are for the props balanced configuration. Given the results for the ARWO station, it was assumed that the C-130J (Slick) aircraft would have shown higher passenger seat vibrations with the props as-is configuration.

External Tanks Removed (C-130J Passengers). Not compared for C-130J (Slick) aircraft.

Altitude and Airspeed (C-130J Passengers). As depicted in Figure C-13, a similar trend was observed in the 16-Hz band for airspeed as described for the ARWO station, i.e., lower accelerations being associated with higher airspeeds. Likewise, in the 100-Hz band, higher accelerations were associated with higher airspeeds (Figure C-14). At 100 Hz, higher accelerations tended to occur at higher altitudes depending on the location and direction of the measurement.

Throttle Setting (C-130J Passengers). In general, the seat pan and seat base accelerations associated with selected throttle settings fell within the ranges observed at level flight with constant airspeed. As noted previously, in some cases, higher magnitude low frequency vibration was observed for the throttle setting conditions as compared to level flight at constant airspeed.

WC/C-130J Cockpit

Cockpit Vibration and Exposure Assessment

Representative frequency response profiles at the copilot and lower bunk seat pan in the fore-and-aft (X), lateral (Y), and vertical (Z) directions are shown in Figures C-16 and C-17. The figures include the 8-hr, 16-hr, and 24-hr Fatigue-Decreased Proficiency Boundaries (1). No acceleration levels measured in the cockpit exceeded the ANSI S3.18-1979 16-hr Fatigue-Decreased Proficiency Boundaries (1) in any direction for any aircraft configuration and flight test condition between 1 and 80 Hz. The third-octave analysis showed that peak responses in the cockpit measurements occurred in the 16-Hz third-octave band and the 100-Hz third-octave band, regardless of the direction of measurement, similar to the results at the ARWO station in the WC-130J and at the passenger locations in the C-130J. Again, there tended to be higher magnitude low frequency vibration (less than 10 H) for the throttle setting conditions.

Figures C-18 and C-19 include the mean copilot and bunk seat base and seat pan accelerations for the props as-is and props balanced configurations in the 16-Hz and 100-Hz frequency bands, respectively. In the 16-Hz band, the copilot seat base and seat pan showed the highest vibration occurring in the vertical direction, particularly for the props as-is configuration. As with the ARWO station, balancing the props tended to reduce the seat vibrations, most notably in the vertical direction. The bunk showed no substantial effect of balancing the props on the 16-Hz band accelerations. The bunk vertical vibrations (seat base and seat pan) in the 16-Hz frequency band were notably lower as compared to the copilot. In the 100-Hz frequency band, the highest copilot seat pan accelerations were observed in the fore-and-aft (X) direction. At the bunk, the highest seat pan accelerations were observed in the lateral direction. At the seat base, the bunk 100-Hz vertical vibrations were notably higher as compared to the copilot. Given the differences between the two cockpit seats, it was difficult to compare the seat base vibrations at these two locations. Although the occupant could affect the seat pan measurements due to seating posture and weight, the seat pan measurements should reflect, to some extent, differences in the vibration transmission characteristics of the two seating surfaces (copilot vs bunk seats).

Comparison of WC/C-130J Seat Vibrations

In addition to the cockpit seat accelerations, Figures C-18 and C-19 also include the mean seat accelerations measured at the ARWO station in the WC-130J and at the center and side passenger locations in the C-130J. The figures show that the lowest vibrations above 10 Hz occurred in the cockpit with a few exceptions for the bunk location. The most dramatic differences occurred in the 100-Hz frequency band. The high floor vibrations measured at the C-

130J passenger locations (particularly at the center location) are quite obvious, as are the high vibrations occurring at the seat pan for the side passenger location. No dramatic differences were observed in the vibrations occurring below 10 Hz among the locations. Interestingly, once the props were balanced, the ARWO 16-Hz seat vibrations tended to be more similar to the cockpit vibrations for the props as-is configuration, particularly the copilot levels and particularly in the fore-and-aft (X) and vertical (Z) directions.

DISCUSSION

Human Vibration Exposure Criteria

The results showed that none of the 16-Hz seat pan vibration levels exceeded the 16-Hr Fatigue-Decreased Proficiency Boundaries defined in the ANSI S3.18-1979 standard (1). The comparison to the ANSI (1) criteria was set forth in the original Test Plan. One issue of concern was how to interpret the levels of vibration occurring in the 100-Hz frequency band, given the 1 – 80 Hz frequency range limit in the exposure standard. Both the horizontal and vertical human sensitivities above 10 Hz are approximated by a constant velocity curve which would provide for the extrapolation outside the 1 – 80 Hz range. However, the ANSI S3.18-1979 (1) explicitly states that the guide should not be extrapolated to frequencies outside of this range. Since the limits are given for one-third octave frequency bands, the 80-Hz band would include the frequency range of approximately 70.8 – 89.2 Hz. While this range is below the 102 Hz frequency associated with the blade passage frequency, as an approximation, the data were compared to these criteria. Using the 16-Hr 80-Hz Decreased-Fatigue Proficiency Boundaries (5.4 m/s^2 rms for horizontal vibration and 1.91 m/s^2 rms for vertical vibration) (1), Figures C-7 and C-8 show that none of the ARWO seat pan accelerations exceeded these limits. Figures C-14 and C-15 show that none of the center passenger seat pan accelerations exceeded the 80-Hz criteria. The side passenger seat pan lateral (Y) and vertical (Z) accelerations did not exceed the 80-Hz criteria. However, the fore-and-aft (X) seat pan accelerations for the side passenger did exceed the 80-Hz horizontal criteria for several conditions. These results emphasize the relatively high vibration occurring at the left side passenger location.

Although not considered for the assessment of the WC/C-130J vibration exposures in the Test Plan, the ANSI S3.18-1979 (1) also includes Reduced Comfort Boundaries which are calculated by dividing the acceleration criteria for the Fatigue-Decreased Proficiency Boundary by 3.15. The Reduced Comfort Boundary (1) primarily addresses difficulties in eating, reading, and writing in transport vehicles. Considering the highest vibrations for the props as-is configuration (16-Hz peaks in the WC-130J aircraft) and props balanced (16-Hz and 100-Hz for both the WC-130J and C-130J aircraft) and for the synchrophaser on configuration, none of the seat pan horizontal vibrations in either aircraft exceeded the 8-Hr Reduced Comfort Boundary. For the props as-is configuration, the ARWO vertical seat pan acceleration did not exceed the 4-hr limit; all other values being less than the 8-hr limit. Comparing the 100-Hz peaks to the 80-Hz Reduced Comfort Boundaries, all seat pan accelerations were less than the 16-hr limits except for the horizontal side passenger seat pan where high accelerations were observed. The fore-and-aft (X) seat pan accelerations were less than the 1-hr limit, while the lateral (Y) levels were less than the 4 Hr limit. The relevance of these findings is not clear since the greater concern was the ability of the crew members to effectively perform more complicated tasks.

The minimal effect of the WC/C-130J vibrations relative to the ANSI S3.18-1979 (1) does not support the reports of annoyance and discomfort by the crew members and their concern about adequately performing their jobs during prolonged exposures. Historically, there has been the issue of whether the human sensitivity predicted by the vibration standards weighting curves can be generally applied to all exposure environments. In particular, the results of this study suggest that the annoyance and discomfort resulting from higher frequency vibration associated with propeller-driven aircraft propulsion systems is not adequately addressed by the current standards. The Air Force Research Laboratory, as part of a Memorandum of Agreement with the Naval Health Research Center, has recently evaluated the human vibration aboard the Navy E-2C Hawkeye aircraft (4). The evaluation was prompted by the results of a survey in which crew members reported annoyance, fatigue, and back pain on aircraft which had undergone upgrades to their propulsion systems. As with the WC/C-130J, the highest vibrations were associated with the rotor speed and blade passage frequency but were shown not to be of any consequence to the aircrew health, performance, or comfort. These results warrant further investigation of human vibration sensitivity in flight environments associated with military propeller-driven aircraft in order to formulate exposure criteria and develop mitigation strategies for minimizing the human vibration effects.

It should be mentioned that the ANSI national standard was based on the International Standards Organization ISO 2631-1 Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration – Part 1: General Requirements (1978). The ISO 2631-1: 1997 (2) is the most recent revision of the standard. The major difference between the 1997 revision and earlier versions (1978 and 1985) is the elimination of the concept of fatigue-decreased proficiency and the assumption that the effects on humans were similar for health, working proficiency and comfort. The standard claims that this was not supported by laboratory research. However, the standard does claim that the "guidance and exposure boundaries recommended in ISO 2631-1:1985 were safe and preventive of undesired effects" (ISO 2631-1: 1997) (2). The ISO 2631-1:1997 (2) uses the overall weighted acceleration to assess the exposures relative to comfort, perception, and health. The ANSI S3.18-1979 (1) does provide a similar method which uses the overall weighted acceleration level to assess the exposure in terms of the various boundaries. Regardless of the differences between the two standards, the weighting curves are similar and expected to produce similar results.

Preliminary Target Vibration Levels

Since the annoyance experienced by the crew members and passengers aboard the WC/C-130J were below the 16-Hr Fatigue-Decreased Proficiency Boundary (1), the question is raised as to what levels would be acceptable exposures for individuals located in the vicinity of the propeller plane. The only documented exposures known to be acceptable at this time occurred in the cockpit locations, the highest levels occurring for the light aircraft with the props as-is. Since the seat pan measurements reflected the vibration at the interface between the occupant and seating system, the copilot seat pan measurements for the props as-is configuration would provide the means for establishing preliminary vibration target levels. As mentioned previously, the vibrations below 10 Hz were similar between the cockpit and cargo locations, so the target levels should focus on the vibrations occurring in the 16-Hz and 100-Hz one-third octave frequency bands. Tables B-2 and B-3 list the mean copilot seat pan data +/- one standard deviation in the 16-Hz and 100-Hz frequency bands, respectively, for the light aircraft and props as-is configurations. The means include both synchrophaser off and on data and the measurements made at airspeeds of 180 KIAS, 220 KIAS, and MCP KIAS for all tested altitudes. Also included are the mean seat pan data +/- one standard deviation for the WC-130J ARWO station for the light aircraft, props as-is and balanced props, and the C-130J center and side passengers for the balanced props configuration. Figure C-20 illustrates the mean target data and the mean ARWO and passenger data in the 16-Hz and 100-Hz frequency bands for comparison. Those levels requiring reductions in the acceleration levels to meet the target seat pan accelerations are marked with an asterisk. It is noteworthy that, with the props balanced, only the Y-axis vibration at the ARWO station exceeded the target levels in the 16-Hz frequency band.

CONCLUSIONS

1. Although the seat pan vibrations in both the WC-130J (ARWO station) and C-130J (center and side passenger seats) were below the 16-hr Fatigue-Decreased Proficiency Boundary, the ANSI criteria relating to the performance of tasks do not appear to be effective for assessing the annoyance and possible fatigue related to prolonged exposures to higher frequency vibration above whole-body resonance (greater than 10 Hz). In addition, the ANSI criteria are restricted to the 1 – 80 Hz frequency range. Conducting an assessment relative to the Reduced Comfort Boundary shows that the 16-hr limit would be exceeded in several cases. However, the Reduced Comfort Boundary applies only to such tasks as eating, reading, and writing and does not address fatigue.

2. The jitter reported by the co-pilot and ARWO was most likely due to display image electronics and not directly to vibration. ARWO vertical display vibration was below the avoidance region given in Section 5.8.4.2, Figure 42, of the MIL-STD-1472C (1984) (3) for equipment vibration. There were no reports of visual blurring of the display during the test flights. The preliminary Lockheed Martin data did suggest that there was relatively high lateral rack vibration.

3. Altitude and airspeed showed some trends in the data. During actual operations, it is expected that the flight scenario would include multiple altitudes and airspeeds. It was concluded that these two flight test conditions did not play a major role in affecting the human vibration.

4. Lower vibration was observed in the heavier aircraft. It is assumed that aircraft weight is not a controllable factor during normal operations. However, given the results for the ARWO station, the vibration might be expected to increase as the aircraft burns fuel. The absence of the external tanks appeared to have no effect.

5. Trends in the vibration relative to the throttle setting were very difficult to assess. These data may not have been consistently collected given the subjectivity involved in initiating the measurement. However, the levels appeared to fall within those levels reported for the constant altitude and airspeed conditions above 10 Hz. There was a tendency for higher vibration below 10 Hz with the throttle setting conditions but none exceeded the ANSI 16-Hz Fatigue-Decreased Proficiency Boundary.

6. Dynamically balancing the propellers did reduce the 16-Hz third-octave band vibration at the ARWO station. This was particularly advantageous for the vertical vibration where the seat pan accelerations were near the 16-hr limit in several cases for the props as-is configuration. Likewise, in the case where the seat base exceeded the 16-Hr Fatigue-Decreased Proficiency Boundary (4000 feet PA, 200 KIAS), the level was reduced to below the boundary (note in Figure C-7.) As reported by other members of the test team, the props as-is configuration on the tested aircraft was not the worst case of unbalanced propellers on the WC/C-130J, and the balanced props configuration was not the best case. It was speculated that even greater reductions in the 16-Hz vibration might be realized with improved balancing techniques. It was also assumed that the 16-Hz vibration levels at the passenger locations (C-130J) were higher prior to balancing the propellers.

7. The 100-Hz band vibration associated with the blade-passage frequency was minimally affected by aircraft configuration or flight test condition. It was concluded that the vibration at

these higher frequencies may be a major contributor to the crewmember and passenger annoyance, particularly once the props were balanced. It is cautioned that the relative contribution to occupant annoyance between the lower frequency components associated with the rotor speed and the higher frequency components associated with the blade passage frequency cannot be determined from the data collected in this study, nor from the relative human frequency sensitivities prescribed in the ANSI standard.

8. The high fore-and-aft seat pan acceleration occurring at the left passenger seat appeared to be primarily due to the direct transmission of sidewall vibration to the seat via the attachment mechanism.

9. The lowest vibration levels occurred in the cockpit and were considered acceptable by the occupants. These data can be used as preliminary target levels for reducing the cargo vibration to acceptable levels. The extent to which this can be accomplished is not known at this time.

RECOMMENDATIONS

The following recommendations are based on the assumption that relocating the DSO and ARWO stations outside the propeller plane is not an option. It is also assumed that locating the passenger seats in the propeller plane is necessary for optimizing mission objectives. The following recommendations are aimed at reducing the vibration at the DSO and ARWO stations in the propeller plane of the WC-130J, and at the passenger locations in the propeller plane of the C-130J. The mitigation strategies described below are based on a hierarchical approach; first attempting to reduce or isolate the vibration at the source (propulsion system). If this is not feasible or practical, mechanisms or processes should be considered which could potentially reduce the vibration transmitted via the various support structures or equipment located between the source and the occupant (such as the seating system.)

1. Balance the propellers. As shown in Figure C-20, balancing of the propellers was associated with a substantial reduction in the propeller plane vibration; in both the Weatherbird

and Slick aircraft accelerations in at least two of the three orthogonal directions were reduced to or below the preliminary target levels. It is recommended that a requirement, specification, and procedure be established for the periodic dynamic balancing of the propellers. As part of the development, the effects of other factors on propeller balance, including weather and flight conditions, and the extent to which propeller balance can be achieved, need to be investigated. This activity will have a primary influence on reducing the vibration associated with the rotor speed (17 Hz).

2. Optimize synchrophaser function. The results showed that the synchrophasers were functioning to maintain a relatively constant angle between propeller blades. However, there appeared to be no effect of synchrophaser function on the measured human vibrations. Unlike the C-130H aircraft, the propeller speed control in the WC/C-130J is not affected when the synchrophaser is turned off. In the previous H-model, turning off the synchrophaser would cause noticeable vibration. The question had been raised regarding the selection of propeller angles in the J model. LM Aero researched this topic and found that the angles were selected based on meeting field noise requirements. Therefore, it is not known whether the angles occurring during the data collection were optimal for minimizing the vibrations at the blade passage frequency (102 Hz). It is recommended that an investigation be undertaken to determined to what extent optimum blade angles could reduce the 102 Hz vibration. This is currently under investigation by LM Aero and could effectively reduce both the noise and vibration associated with the blade passage frequency.

3. Investigate passive and active mechanisms for isolating the vibrations. If the procedures mentioned above do not adequately reduce the human vibration by reducing the vibration at the source, the next approach should be the investigation of various techniques directed at damping the vibration entering the aircraft via the fuselage. LM Aero has suggested the possible use of dynamic absorbers for damping the 102-Hz vibration in the fuselage structure.

4. Isolate the DSO/ARWO (WC-130J) and Passengers (C-130J). With the observed lowering of the ARWO seat pan fore-and-aft (X) and vertical (Z) accelerations in the 16-Hz band with dynamic propeller balancing, it is practical to direct additional mitigation efforts to the

higher frequency range in the vicinity of the blade-passage frequency. Any mitigation strategy should consider all three directions, particularly since cross-talk between axes is not understood at these higher frequencies (i.e., the effect that vibration in one axis has on the transmission of vibration in other axes). In the Weatherbird (WC-130J), it is recommended that techniques be investigated, either active or passive, that would isolate the ARWO and DSO pallets from the aircraft. Relative motion between the floor and pallet can be assessed using the Lockheed Martin equipment data (at least in the vertical direction). A cursory review of the equipment data suggested that there were no substantial differences in the vertical vibration levels between the floor, pallet, and seat base at the ARWO station, making it feasible to reduce them to acceptable levels. However, the relative horizontal motions (fore-and-aft (X) and lateral (Y)) between the pallet and the floor and the pallet and the seating structure are not known.

Another approach is to reduce vibration of the seat structure. The seat base is attached to a smaller pallet that, in turn, is attached to the main pallet (Figure 1a). The attachment is via a rail system that allows for seat movement in the horizontal plane. It is suspected that this arrangement contributes to relative motion between the smaller pallet and the main pallet, as well as between the seat itself and the small pallet. The need for the seat adjustment may render it difficult to reduce any relative motion.

Seat cushions can dampen higher frequency vibration in the vertical direction, but the effects on horizontal vibration have not been assessed to any great extent. The ARWO 100-Hz seat pan vertical (Z) vibrations were the lowest, directing attention to minimizing the horizontal directions. However, the 100-Hz seat back vertical (Z) vibrations were notably higher than at the seat pan (Figure C-8). Unfortunately, the relative sensitivity of the occupant to the frequency, direction, and location of vibration (seat pan vs. seat back) is not understood, rendering it difficult to establish seating material design criteria for the Weatherbird.

The preliminary equipment data suggested that there was relatively higher lateral vibration in the rack as compared to the seat at the ARWO station at 16-Hz. The effect of the rack vibration on the horizontal motion of the display is unknown. However, no visual blurring was reported during this study. Minimizing vibration of the pallet should also reduce the rack vibration, but directing mitigation efforts to the seating system would not. The Lockheed Martin preliminary data showed substantially higher vibration at the ARWO rack as compared to the DSO rack in the lateral direction (16-Hz), suggesting that the ARWO rack also be mounted on springs.

In the Slick (C-130J) aircraft, the seats are not mounted on a pallet but attached directly to the floor and sidewall. Although the props as-is configuration was not tested in the Slick aircraft, relatively low accelerations were observed at the passenger seat pans in the 16-Hz frequency band. As shown in Figure C-20, there were substantially high vibrations occurring at the sidewall location. The mitigation strategies described in Items 2 and 3 above may not be effective enough to adequately reduce passenger seat vibration. It is recommended to evaluate new or improved methods/materials for mounting or attaching the seats. In particular, the current mounting of the side seat allows for the direct transmission of vibration from the sidewall to the side seat, causing very high levels of vibration in the 100-Hz frequency range. Additional reductions could possibly be realized by using a different fabric and/or with some seat padding or cushion.

The vertical floor vibration along the centerline was relatively high and noticed by the passengers, particularly in the C-130J aircraft. As mentioned, the floor is sectioned. Other methods, in addition to the mitigation strategies described in Items 1, 2, and 3, may be required for reducing this vibration.

The above recommendations involve the reduction of vibration at several locations in both the WC-130J and C-130J aircraft. The question is raised as to how much the vibration should be reduced. Although the cockpit data provided preliminary target levels, these levels may be lower than those required for acceptability and may also not be easily obtained, particularly in the 100-Hz frequency band. The cockpit data are being used only because the levels are known to be acceptable by the aircrew and are documented. It is recommended that additional data be collected outside the prop plane in the cargo area. It is speculated that levels occurring toward the back of the cargo area may be acceptable but need further evaluation and documentation. Another (and more rigorous) approach is to conduct controlled laboratory studies to investigate the effects of vibration frequency, direction, and location on human vibration perception and biodynamics in propeller-driven aircraft in order to establish appropriate guidelines for human exposure in this flight environment.

REFERENCES

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4. Smith, S. D., Artino, Jr., A. R., Newman, R. J., and Hodgdon, J. A. Human vibration analysis in a military propeller-driven aircraft. *Proceedings of the 36th United Kingdom Meeting on Human Responses to Vibration,* held at Centre for Human Sciences, QinetiQ, Farnborough, UK, 12-14 September, 2001.

APPENDIX A

Deficiency Reports

DEFICIENCY REPORT FB2805000286

FILE NUMBER :: 6
ACCESSION NUMBER :: 511100
DATE OF LAST EDIT :: 2000-02-24
DATE INPUT TO INFOCEN :: 2000-02-23
ORIGINATOR ADDRESS :: 418 FLTS
ORIGINATOR INSTALLATION :: EDWARDS AFB
ORIGINATOR CITY, STATE, ZIP:: CA 93524
ORIG NAME/PHONE NR/DT SUB :: MAJ STEVE DAVIS
33 FLTS MCGUIRE AFB
ORG PT NAME/PHONE NR/DT VER:: ANN CLARK/DSN 527-7133 x2291
REPORT CATEGORY (1 OR 2) :: 1
OPERATIONAL IMPACT :: OPS EFFECTIVENESS
REPORT CONTROL NUMBER :: FB2805000286
HAZARD CODE :: 3
NATIONAL STOCK NUMBER :: NSL
NOMENCLATURE :: WC-130J
DATE DEFICIENCY DISCOVERED :: 2000-01-28
MANUFACTURER SOURCE :: LOCKHEED MARTIN
MANUFACTURER (CAGE) CODE :: 98897
CONTRACT NUMBER :: F33657-95-C-2055
ITEM NEW OR REPAIRED :: U
OPERATING TIME AT FAILURE :: 0.00
GOVT FURNISHED EQUIP (Y/N) :: Y
QUANTITY RECEIVED :: 0.00
QUANTITY INSPECTED :: 0.00
QUANTITY DEFICIENT :: 0
QUANTITY IN STOCK :: 0
END ITEM MDS :: C-130J
END ITEM SERIAL NUMBER :: C-130J (WC)
ITEM UNDER WARRANTY (Y/N/U):: Y
WORK UNIT CODE (WUC) :: 00000
DETAILS/PROBLEM SUMMARY :: A)CIR PRIOR TO DIF: WHILE IN CRUISE FLIGHT. DETAILS: AN INTENSE LOW FREQUENCY (240-300 Hz) VIBRATION WAS FELT BETWEEN FS 330 AND FS 390 WHILE IN CRUISE FLIGHT. THE VIBRATION WAS INTENSE ENOUGH TO VIBRATE BOTH THE ARWO AND DSO PALLETS. THIS CAUSE A PERCEPTIBLE JITTER IN THE DISPLAYS ON BOTH PALLETS. THIS COULD BE VERY FATIGUING ON THE EYES. WHILE IT IS POSSIBLE TO FOCUS ON THE SCREENS, IT WAS DIFFICULT TO MAINTAIN CONCENTRATION. A WATER BOTTLE PLACED ON TOP OF THE ARWO PALLET HAD ONE INCH WAVES INDUCED BY THE VIBRATION. CYCLING THE PROP SYNC SWITCH HAD NO EFFECT. NEITHER DID VARYING THE THROTTLES. THE POWER WAS AT MAXIMUM CONTINUOUS AND THE GROSS WEIGHT WAS ABOUT 142,000 POUNDS, THE AIRSPEED WAS ABOUT 210 KIAS AT 24,000 FEET. LATER IN THE MISSION (ABOUT FIVE HOURS AFTER TAKEOFF) THE LOW FREQUENCY VIBRATION WAS SUBSTANTIALLY REDUCED AND A HIGHER FREQUENCY BUZZ WAS FELT. AT THIS POINT, THE AIRCRAFT WAS AT 24,000 FEET AND 228 KIAS. SIMILAR VIBRATIONS WERE NOTED ON OTHER MISSIONS AN DIFFERENT GROSS WEIGHTS. ON ONE MISSION, THE WORST VIBRATION OCCURRED DURING CRUISE AT 30,000 FEET AND ABOUT 120,000 POUNDS GROSS WEIGHT. THE VIBRATIONS WERE FELT ON EACH FLIGHT WITH VARYING INTENSITY. THE DSO COMMENTED THAT IT WAS INTOLERABLE TO WORK IN THAT VIBRATION ENVIRONMENT FOR THE LONG WEATHER RECONNAISSANCE MISSIONS. THE ARWO COMMENTED THAT THE VIBRATIONS RANGED FROM TOLERABLE TO VERY UNCOMFORTABLE. IMPACT: THE POSITIONING OF THE ARWO AND DSO PALLETS PLACE THE WEATHER OFFICER AND DROPSONDE

OPERATOR DIRECTLY IN THE GREATEST VIBRATION AREA. THE DSO SEAT HAS A SUBSTANTIAL VIBRATION MUCH LIKE A MECHANICAL VIBRATOR IN SOME HOME CHAIRS. WHILE THIS IS FINE FOR RELAXING AT HOME, IT IS DISTRACTING AND FATIGUING FOR THE DSO. IN ADDITION, THE VIBRATION IS CONDUCTED THROUGH THE BODY TO THE EARS, CREATING A LOUD LOW FREQUENCY NOISE. THE NOISE IS NOT CANCELLED BY THE ACTIVE NOISE REDUCTION HEADSETS (WHICH ARWO AND DSO WERE WEARING) SINCE THE VIBRATION IS CONDUCTED THROUGH THE BODY AND NOT THROUGH THE AIR. BOTH THE ARWO AND DSO NOTED RINGING IN THEIR EARS AFTER THE FLIGHTS, INDICATING THAT THE NOISE IS LOUD ENOUGH TO BE DAMAGING. IT IS NOT CLEAR WHAT EFFECT THE INTENSE VIBRATION WILL HAVE ON LONG TERM RELIABILITY OF THE ARWO AND DSO PALLET EQUIPMENT. ON THE WC-130H, NEITHER THE ARWO OR DSO EQUIPMENT WAS EXPOSED TO THIS VIBRATION ENVIRONMENT DUE TO DIFFERING LOCATIONS OF THE STATIONS. THIS IS A HUMAN FACTORS, OPERATIONAL, DESIGN AND SAFETY DEFICIENCY IMPACTING OPS EFFECTIVENESS, OPS SUITABILITY AND MILITARY UTILITY. C) RECOMM: INVESTIGATE AND TAKE CORRECTIVE ACTION : SUGGEST REDUCE THE VIBRATION IN AND AROUND THE ARWO AND DSO STATIONS.

COUNTRY :: USA
AFLC ITEM MGR/SYSTEM MGR :: FJ
CERTIFYING OFFICIAL/PHON NO:: LTCOL S. CARBAUGH
DSN 527 - 7190 X 3224
QA/EQUIP SPECIALIST/PHON NO:: JACK REAGAN DSN468-7341
QA/EQUIP SPEC OFFICE SYMBOL:: WR-ALC/LB
MIP/PROJECT NUMBER :: WRBLT 00-0007
DATE MIP OPENED :: 2000-02-24
DR/MIP STATUS :: OPEN
MIP PRIORITY :: U
PROJECT SOURCE :: MDR
SUBJECT :: WC-MISSION SYSTEM - HF - EXCESSIVE VIBRATION AT ARWO AND DSO PALLET LOCATION
RECEIPT ACKNOWLEDGEMENT DTE:: 2000-02-24
Originator ID :: clarkaa

DEFICIENCY REPORT FA9107000029

FILE NUMBER :: 6
ACCESSION NUMBER :: 511288
DATE OF LAST EDIT :: 2000-02-25
DATE INPUT TO INFOCEN :: 2000-02-24
ORIGINATOR ADDRESS :: 711 MEADOWS DRIVE, ROOM 253
ORIGINATOR INSTALLATION :: C-130J TEST TEAM
ORIGINATOR CITY, STATE, ZIP:: KEESLER AFB MS 39534
ORIG NAME/PHONE NR/DT SUB :: MSGT HASHAGEN/DSN 597-2468 COMM 228-377-2468/ 2000-01-28
ORIGINATING POINT :: AFOTEC OLKM
ORG PT NAME/PHONE NR/DT VER:: TSGT REICHELT/DSN 597-2470 COMM (228) 377-2470/2000-01-21
REPORT CATEGORY (1 OR 2) :: 2
QA1 OR QAKA/QAKE REPORT :: QA1
REPORT CONTROL NUMBER :: FA9107000029 C130J QOT&E
NATIONAL STOCK NUMBER :: NSL
DATE DEFICIENCY DISCOVERED :: 2000-01-28
MANUFACTURER SOURCE :: LOCKHEED MARTIN CORP
MANUFACTURER (CAGE) CODE :: 98897
MAINTENANCE TYPE :: C
CONTRACT NUMBER :: F33657-95-C-2055
ITEM NEW OR REPAIRED :: U
GOVT FURNISHED EQUIP (Y/N) :: N/A
QUANTITY RECEIVED :: 0.00
QUANTITY INSPECTED :: 0.00
QUANTITY DEFICIENT :: 0
QUANTITY IN STOCK :: 0
END ITEM MDS :: C-130J
ITEM UNDER WARRANTY (Y/N/U):: Y
WORK UNIT CODE (WUC) :: 11000
DETAILS/PROBLEM SUMMARY :: A) CIR PRIOR TO DIFFICULTY: COLD WEATHER DEPLOYMENT AIRCRAFT IN FLIGHT CROSS COUNTRY B) DETAILS: DURING FLIGHT THE AIRCRAFT EXPERIANCES A STRONG LOW FREQUENCY VIBRATION CENTERED IN THE CARGO COMPARTMENT AREA BENEATH THE WING BOX. THE VIBRATION SEEMS TO BE SOMEWHERE IN THE 10-30 HZ RANGE. IT DIMINISHES AS IT RESONATES FOREWARD AND AFT, BUT IT IS VISIBLY NOTICABLE IN THE FLIGHT DECK. THE A.M.U. COVER ON THE DASH VISIBLY VIBRATES. THE VIBRATION OCCURS IN ALL FLIGHT RANGES, ATTITUDES AND ALITITUDES, BUT VARIES IN AMPLITUDE. THE AMPLITUDE MORE THAN DOUBLES WHEN THE AIRCRAFT IS CONFIGURED AND FLYING AT LOW SPEEDS AND HIGH THROTTLE SETTINGS TO INCLUDE TAKEOFF, CLIMBOUT AND APPROACH. THE VIBRATION DIMINISHES FROM THE NORM BY HALF WHEN STARTING A DECENT WITH REDUCED THROTTLE SETTINGS. C) RECOMMENDATIONS: THE POTENTIAL FOR AIRFRAME LIFE LIMITING DAMAGING EFFECTS FROM HIGH AMPLITUDE LOW FREQUENCY VIBRATIONS ON THE AIRFRAME ARE PROFOUND AND SHOULD BE GIVEN AS MUCH VISIBILITY AS POSSIBLE, INVESTIGATE TO DETERMINE CAUSE AND EFFECTS AND CORRECT
COUNTRY :: USA
AFLC ITEM MGR/SYSTEM MGR :: FJ
COGNIZANT OFFICIAL/PHONE NO:: TSGT REICHELT/DSN 597-2470
CERTIFYING OFFICIAL/PHON NO:: MAJ BROWN/DSN 597-3513
COMM (228) 377-3513
QA/EQUIP SPECIALIST/PHON NO:: GARY HOLLEY, DSN: 468-4769
QA/EQUIP SPEC OFFICE SYMBOL:: WR-ALC/LBPQ
MIP/PROJECT NUMBER :: WRBZZ 00-0188
DATE MIP OPENED :: 2000-02-25

DR/MIP STATUS :: OPEN
MIP PRIORITY :: R
PROJECT SOURCE :: MDR
SUPP/ACT POINT ACTIVITY :: JASC/GRB
SUPPORT POINT POC :: MAJ MAZIARZ, DSN: 986-9472
SUPP/ACT POINT REPLY DATE :: 2000-04-05
1590 ADDITIONAL INFO :: FOR MORE DETAIL OR QUESTIONS EMAIL MSGT HASHAGEN AT JOSEPH.HASHAGEN@AFOTEC.AF.MIL
SUBJECT :: AIRCRAFT LOW FREQUENCY VIBRATION
RECEIPT ACKNOWLEDGEMENT DTE:: 2000-02-25
Originator ID :: carl.reichelt@afotec.af.mil
ACTION SUMMARY :: REPORT FORWARDED TO MAJ JOHN MAZIARZ, DSN: 986-9472 AND TOBIN DENNY, DSN: 986-5335, AT ASC/GRB, WPAFB, OH, THE C-130 DEVELOPMENT OFFICE, FOR INVESTIGATION AND CLOSING ACTION.

APPENDIX B

Tables

Table B-1. 16-Hz One-Third Octave Band Accelerations – Props As-Is vs. Props Balanced

VERTICAL (Z) ARWO SEAT PAN ACCELERATIONS (m/s^2 rms)						
ALTITUDE (Feet PA)	AIRSPEED (KIAS)					
	180		220		MCP	
	As-Is	Balanced	As-Is	Balanced	As-Is	Balanced
4000	0.278	0.081	0.328	0.059	0.192	0.042
10000	0.266	0.072	0.284	0.052	0.191	0.036
18000	0.285	0.091	0.230	0.022	0.140	0.029
24000	0.244	0.082	0.172	0.020	0.172	0.026
30000	0.214	0.140	0.167	0.079	0.167	0.079
Lowest Reduction:	1.5X		Highest Reduction:		10X	

LATERAL (Y) ARWO SEAT PAN ACCELERATIONS (m/s^2 rms)						
ALTITUDE (Feet PA)	AIRSPEED (KIAS)					
	180		220		MCP	
	As-Is	Balanced	As-Is	Balanced	As-Is	Balanced
4000	0.458	0.164	0.514	0.087	0.330	0.098
10000	0.386	0.133	0.466	0.072	0.256	0.084
18000	0.415	0.136	0.356	0.041	0.177	0.065
24000	0.310	0.186	0.217	0.057	0.217	0.069
30000	0.249	0.258	0.189	0.152	0.189	0.152
Lowest Reduction:	1.2X		Highest Reduction:		2.6X	

FORE-AND-AFT (X) ARWO SEAT PAN ACCELERATIONS (m/s^2 rms)						
ALTITUDE (Feet PA)	AIRSPEED (KIAS)					
	180		220		MCP	
	As-Is	Balanced	As-Is	Balanced	As-Is	Balanced
4000	0.156	0.044	0.168	0.027	0.100	0.026
10000	0.150	0.034	0.130	0.033	0.088	0.023
18000	0.124	0.039	0.106	0.018	0.079	0.019
24000	0.124	0.044	0.091	0.016	0.091	0.020
30000	0.122	0.044	0.099	0.034	0.099	0.034
Lowest Reduction:	2.9X		Highest Reduction:		6.2X	

Table B-2. Mean 16-Hz One-Third Octave Band Accelerations (Light Aircraft, Combined Synchrophaser Off/On)

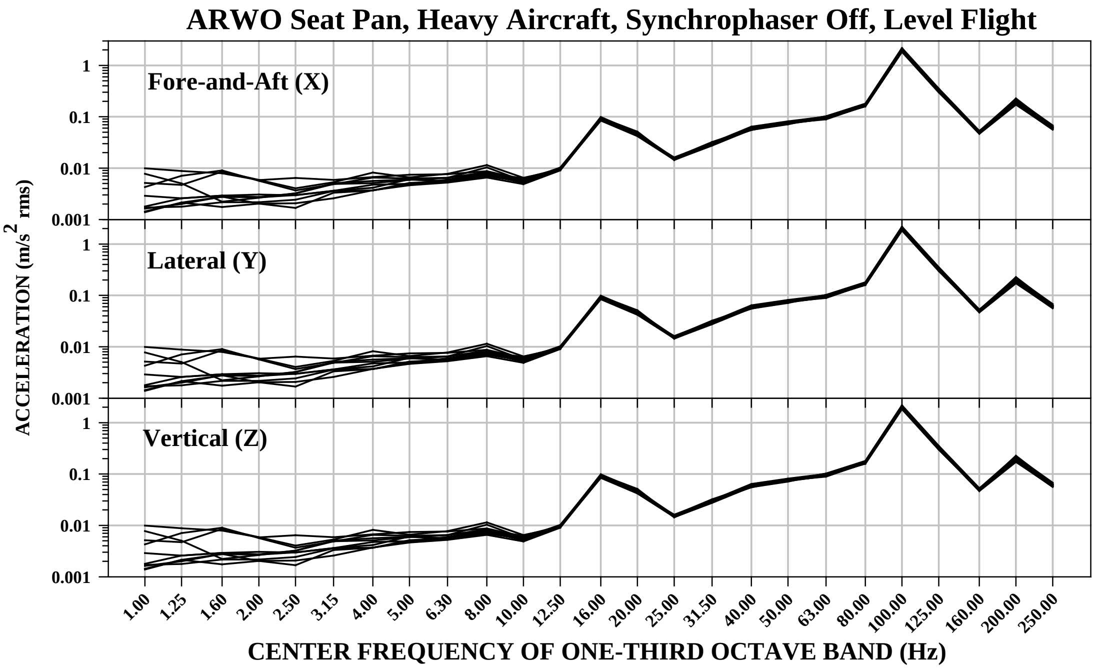
	Copilot Props As-Is		ARWO Props As-Is		ARWO Balanced Props		Center Passenger Balanced Props		Side Passenger Balanced Props	
	m/s^2 rms	1 SD	m/s^2 rms	1 SD	m/s^2 rms	1 SD	m/s^2 rms	1 SD	m/s^2 rms	1 SD
Seat Pan X	0.0275	0.0045	0.1164	0.0270	0.0358	0.0153	0.0530	0.0186	0.0718	0.0398
Seat Pan Y	0.0423	0.0082	0.2798	0.1185	0.1360	0.0575	0.0180	0.0074	0.0154	0.0058
Seat Pan Z	0.1012	0.0299	0.2227	0.0506	0.0723	0.0330	0.0376	0.0216	0.0561	0.0273

Table B-3. Mean 100-Hz One-Third Octave Band Accelerations (Light Aircraft, Combined Synchrophaser Off/On)

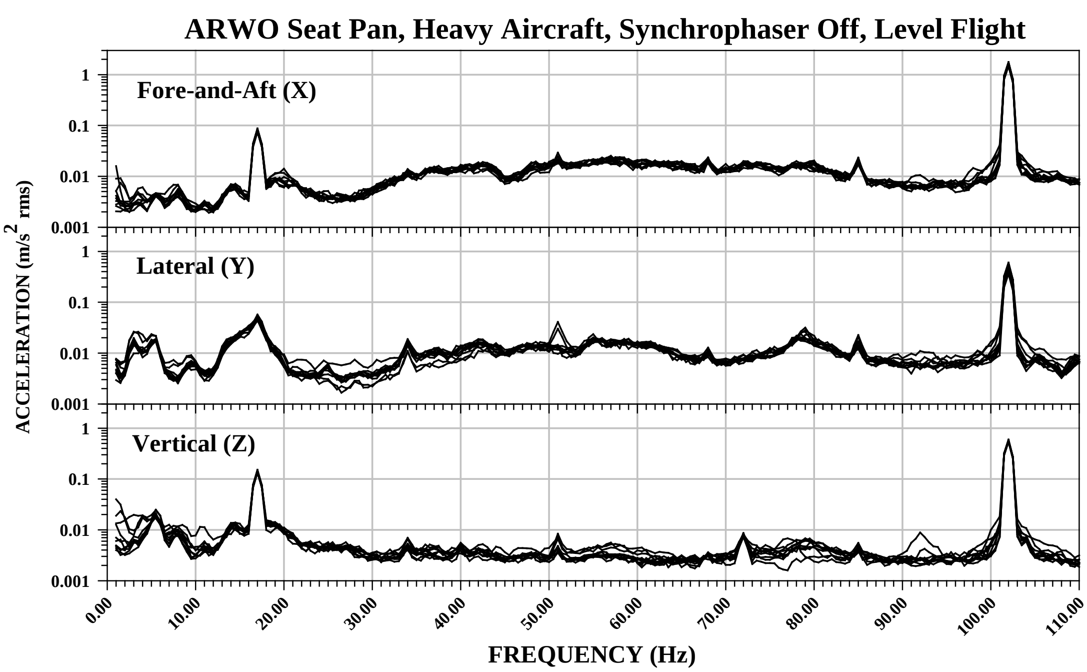
	Copilot Props As-Is		ARWO Props As-Is		ARWO Balanced Props		Center Passenger Balanced Props		Side Passenger Balanced Props	
	m/s^2 rms	1 SD	m/s^2 rms	1 SD	m/s^2 rms	1 SD	m/s^2 rms	1 SD	m/s^2 rms	1 SD
Seat Pan X	0.2720	0.1393	0.8175	0.4162	0.7199	0.3821	0.5741	0.3092	5.0793	2.7703
Seat Pan Y	0.1322	0.0861	0.6061	0.4356	0.5068	0.3461	0.2576	0.1503	1.4174	0.7553
Seat Pan Z	0.0775	0.0400	0.3136	0.1828	0.3333	0.1949	0.2359	0.1821	0.9295	0.4741

APPENDIX C

FIGURES



a.



b.

Figure C-1. ARWO Seat Pan Vibration Reponses During Level Flight: a. One-Third Octave Frequency Bands; b. Constant Frequency Bandwidth, 0.5 Hz

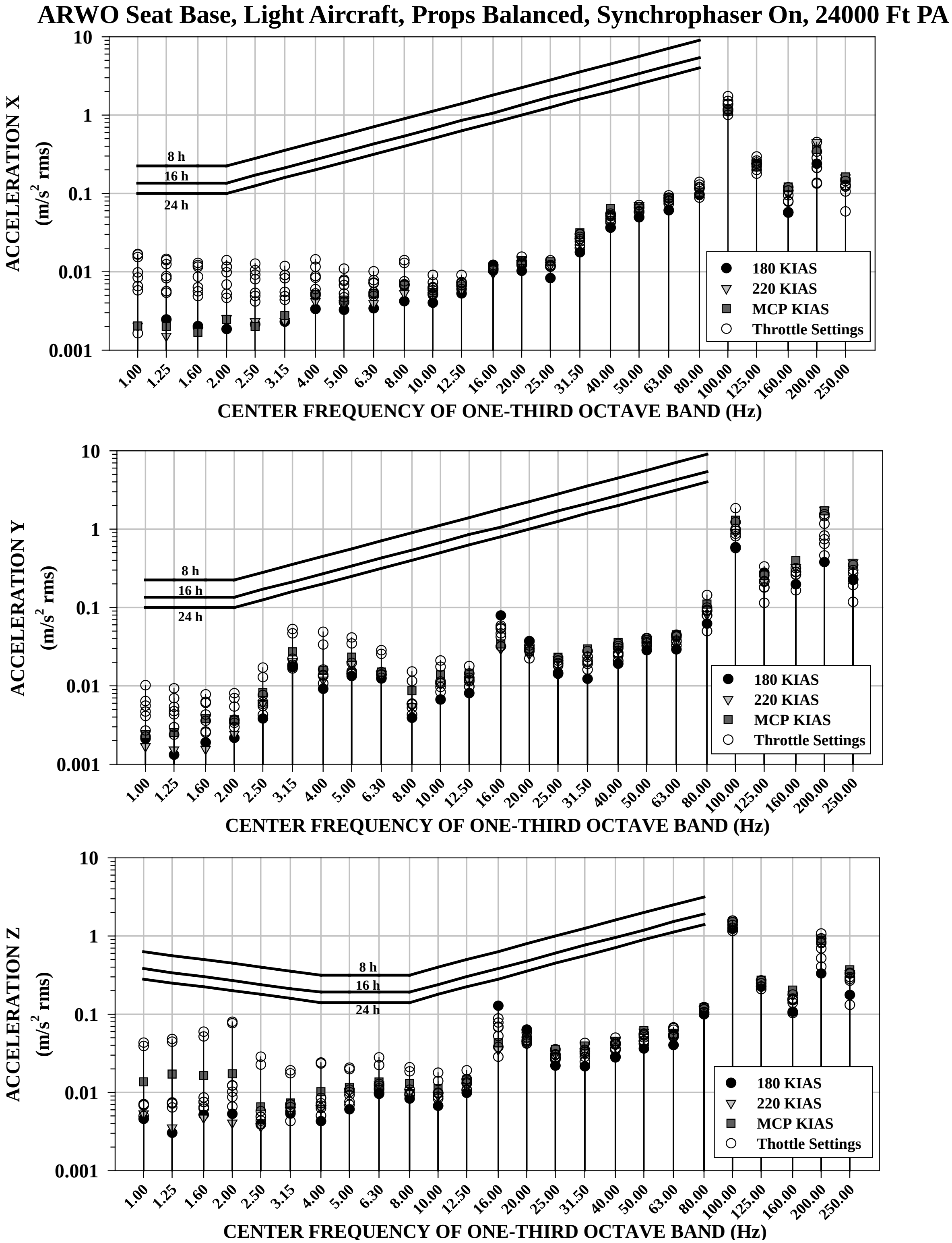


Figure C-2. ARWO Seat Base Fore-and-Aft (X), Lateral (Y), and Vertical (Z) One-Third Octave Band Accelerations

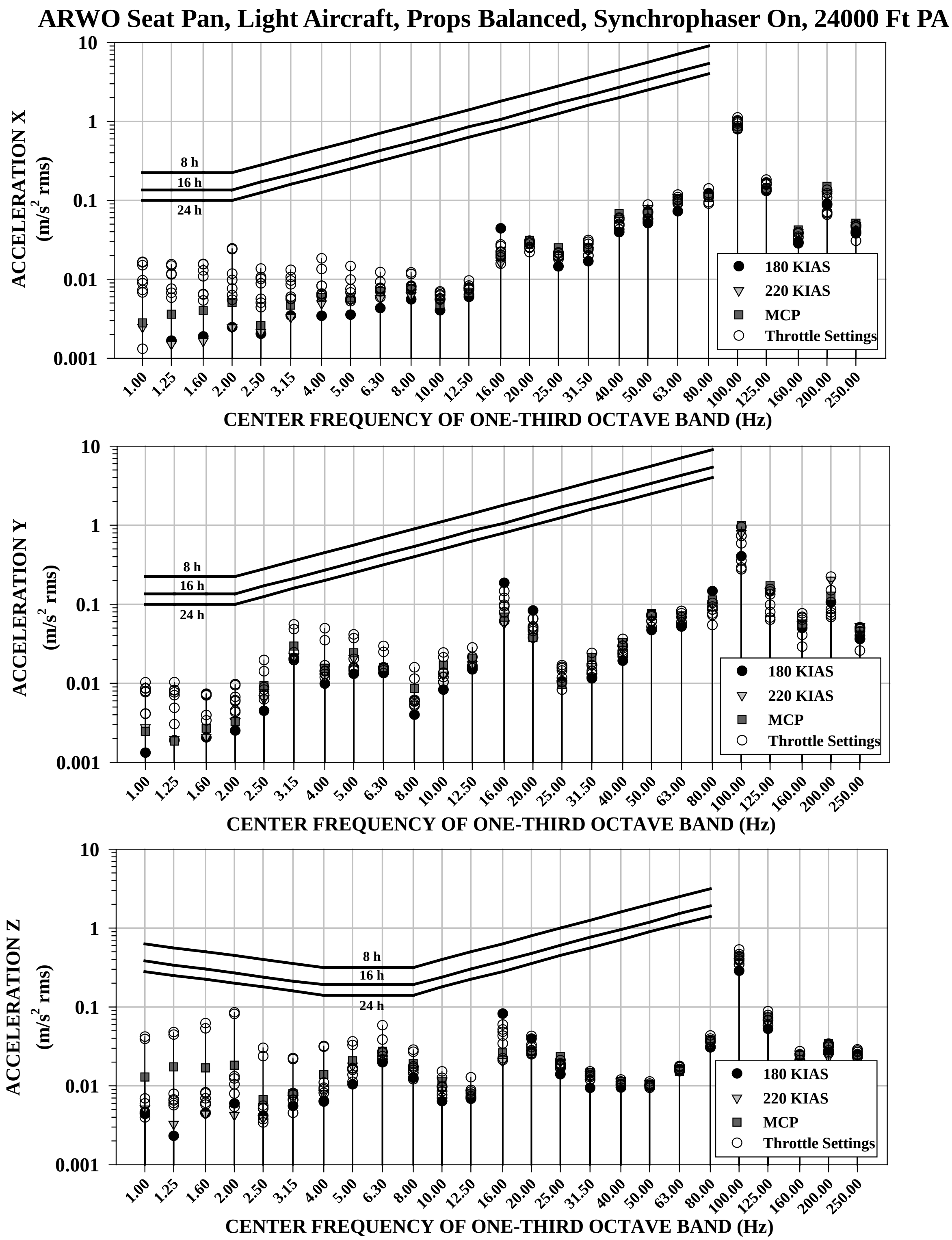


Figure C-3. ARWO Seat Pan Fore-and-Aft (X), Lateral (Y), and Vertical (Z) One-Third Octave Accelerations

ARWO Seat Back, Light Aircraft, Props Balanced, Synchrophaser On, 24000 Ft PA

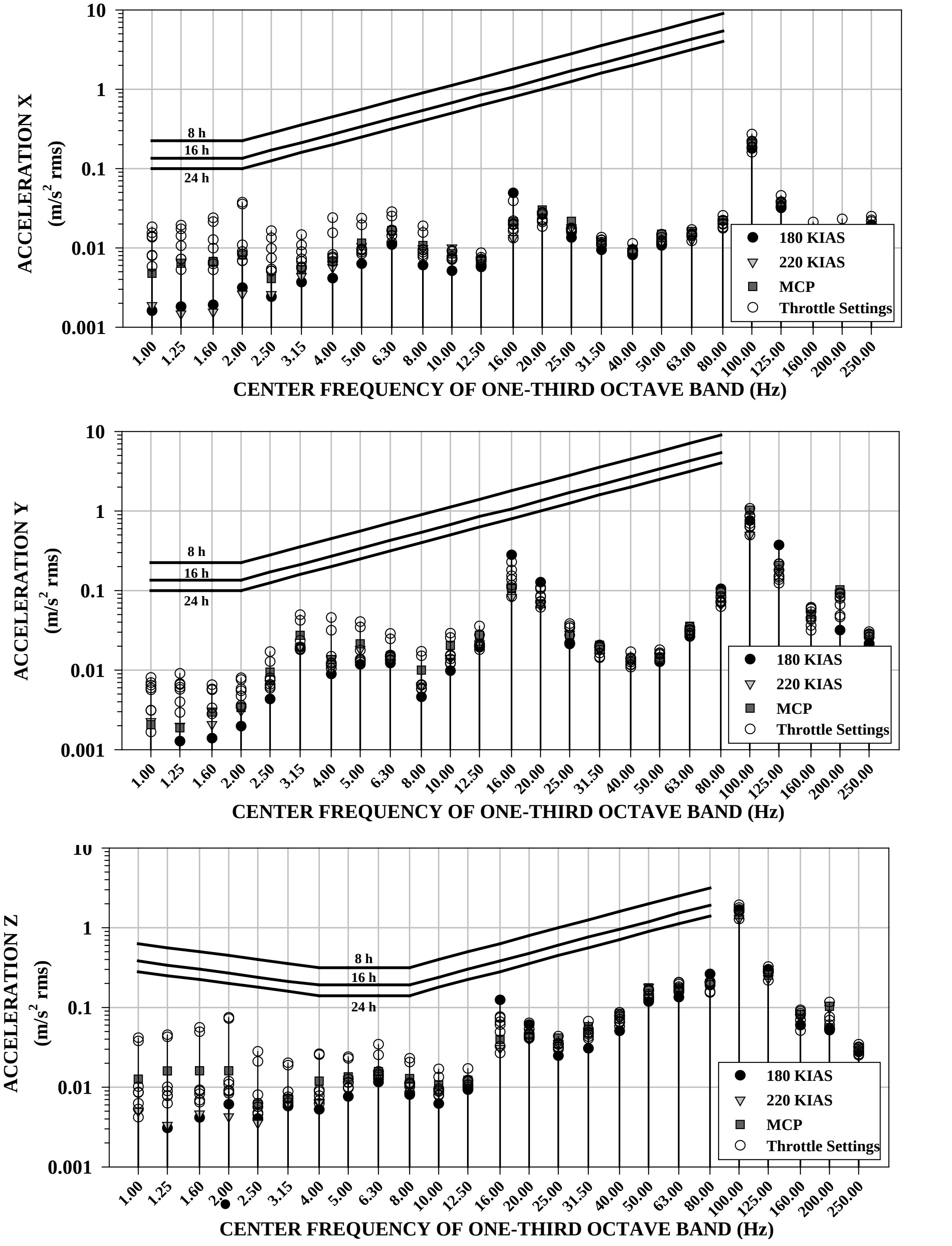


Figure C-4. ARWO Seat Back Fore-and-Aft (X), Lateral (Y), and Vertical (Z) One-Third Octave Accelerations

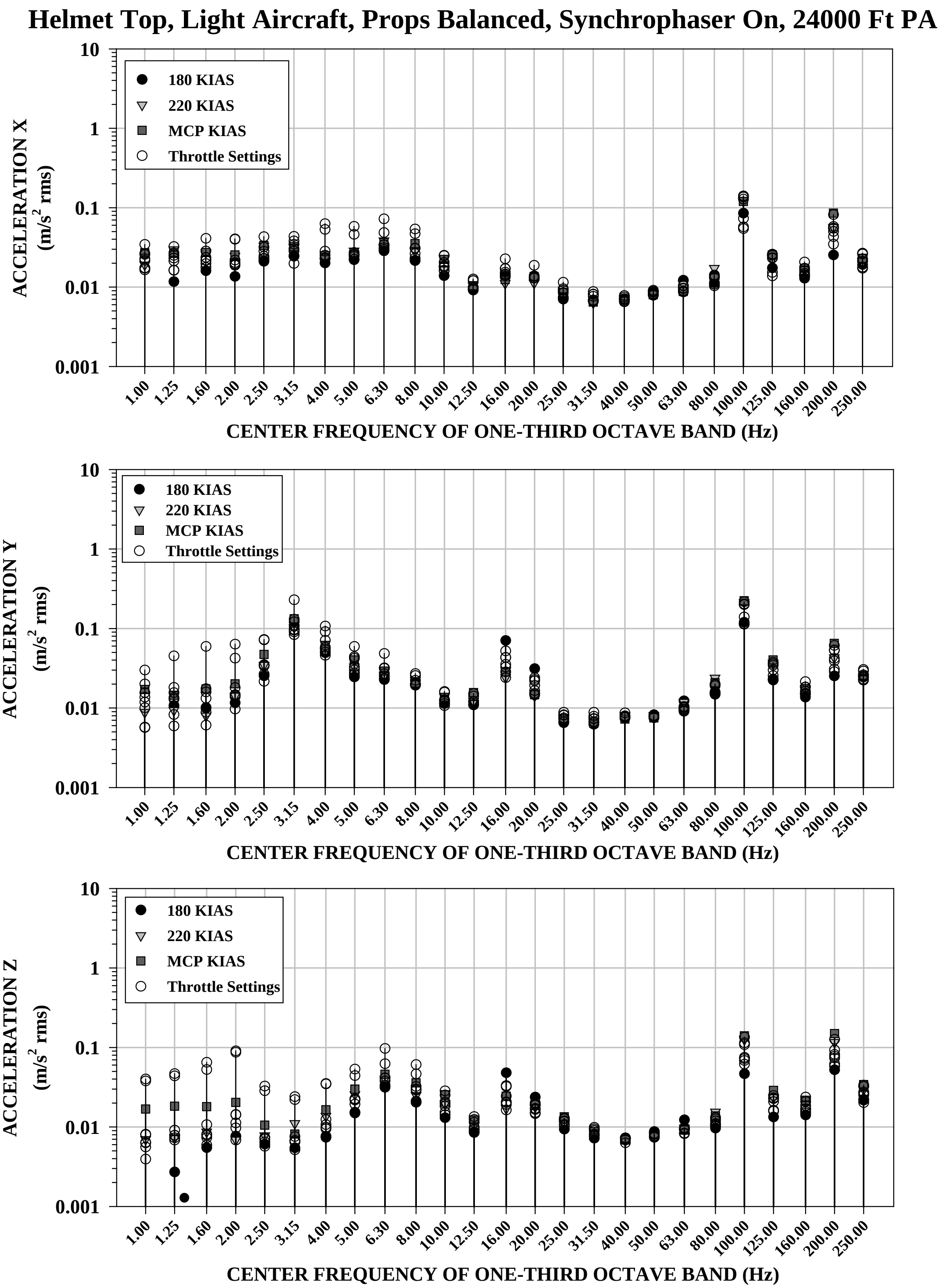


Figure C-5. ARWO Helmet Top Fore-and-Aft (X), Lateral (Y), and Vertical (Z) One-Third Octave Band Accelerations

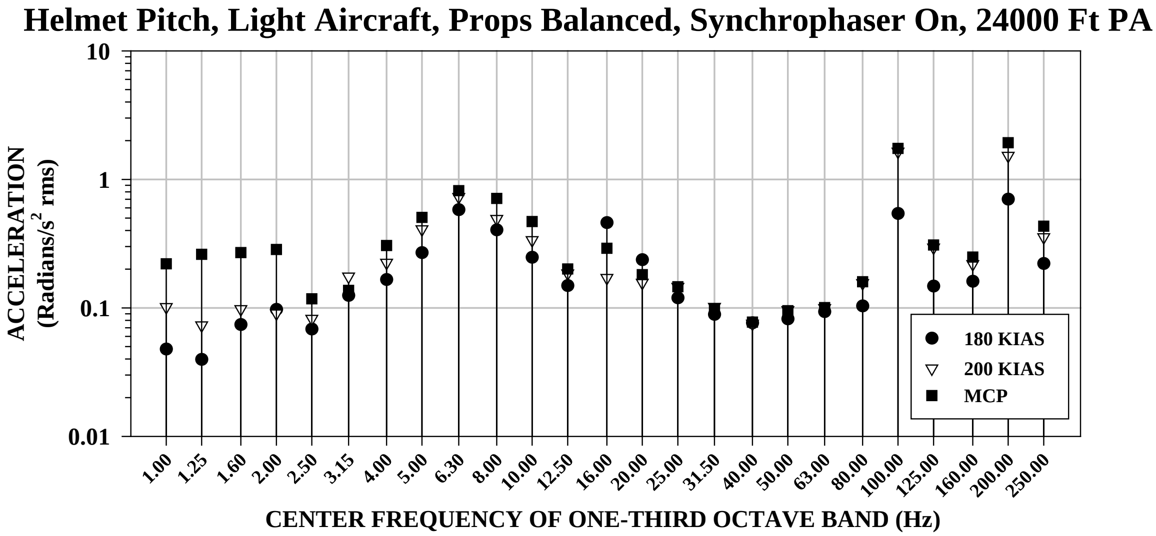


Figure C-6. ARWO Helmet Pitch One-Third Octave Band Accelerations

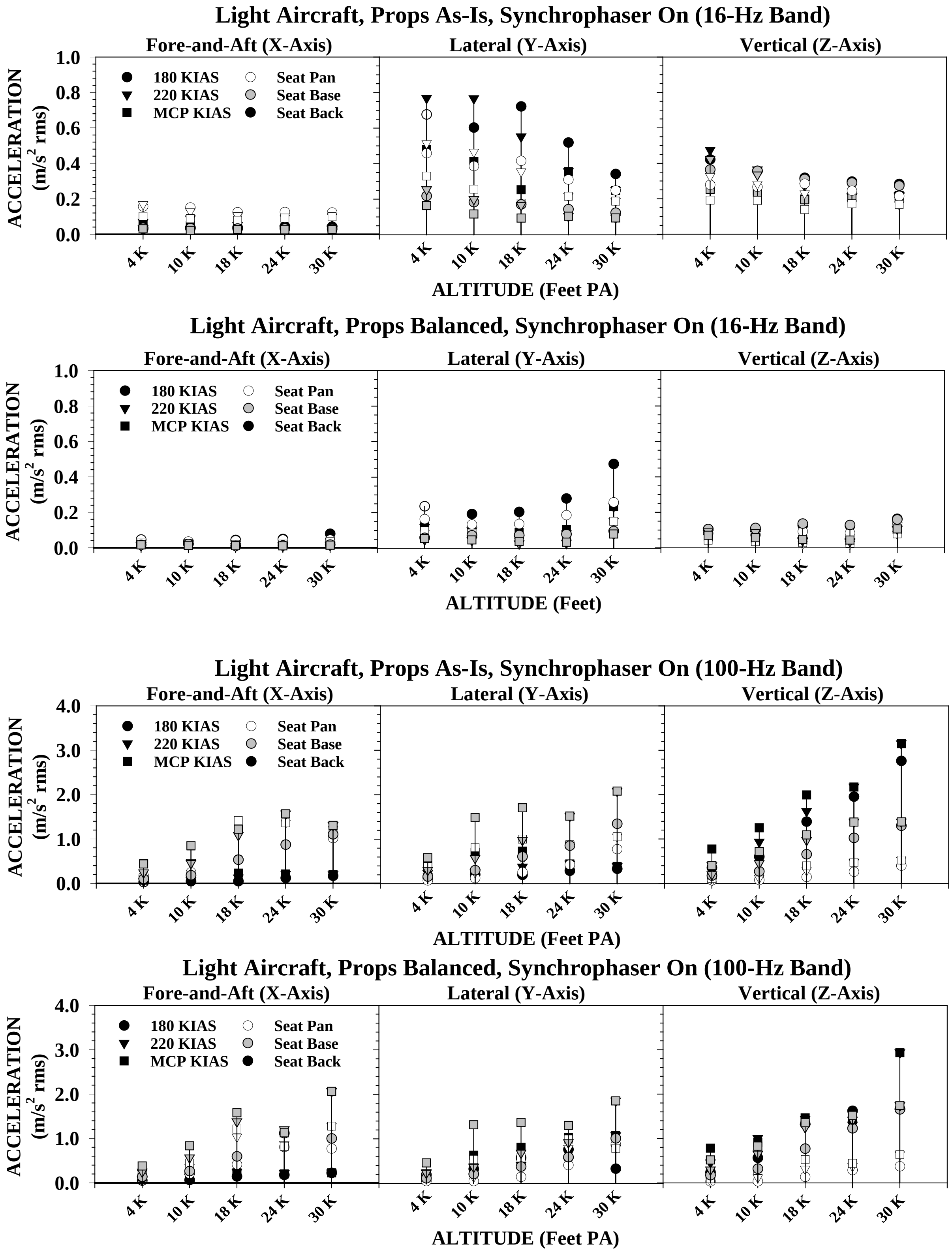


Figure C-7. ARWO Seat 16-Hz and 100-Hz One-Third Octave Band Accelerations

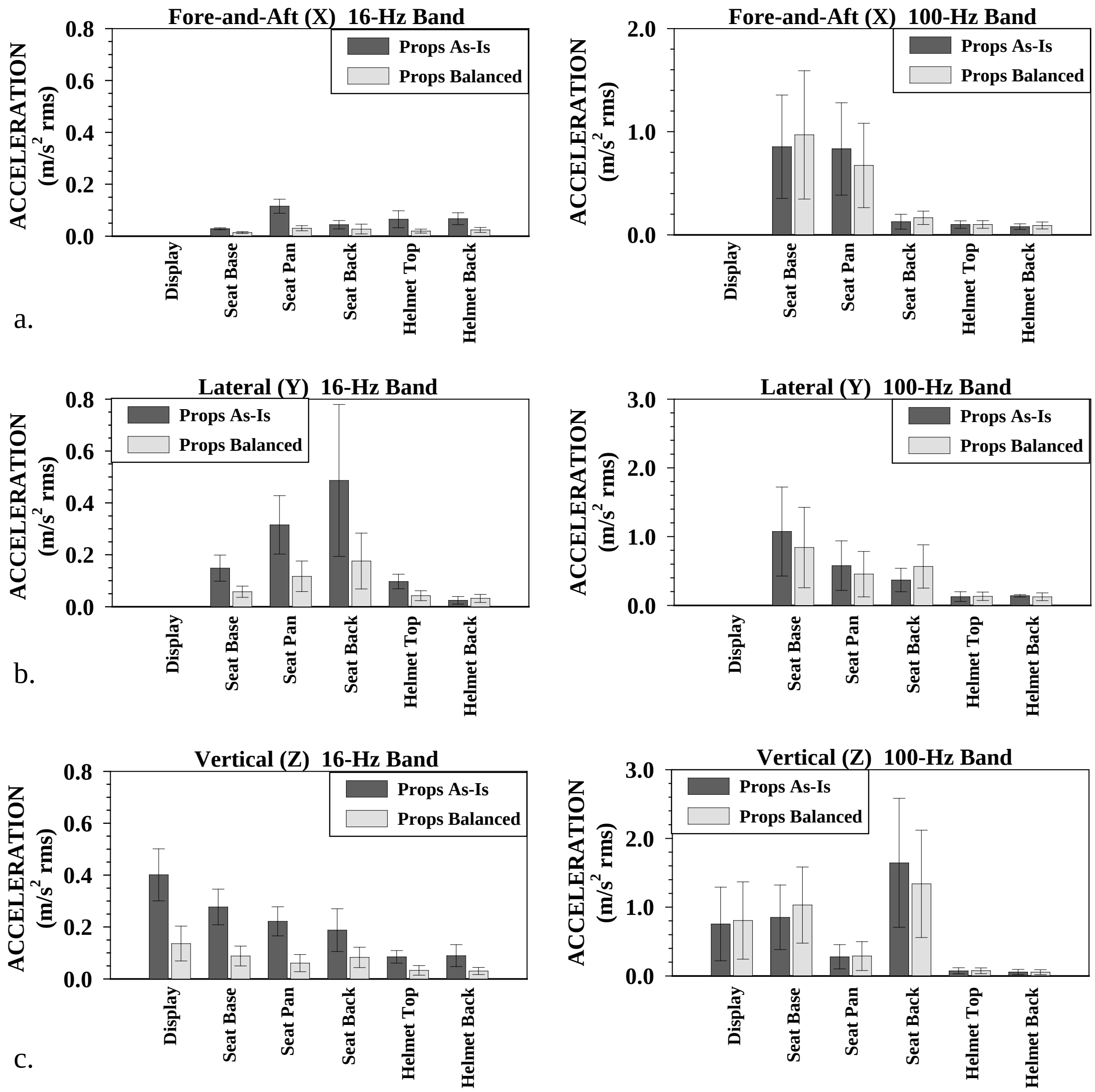


Figure C-8. ARWO Station Mean 16-Hz and 100-Hz One-Third Octave Band Accelerations: a. Fore-and-Aft (X); b. Lateral (Y); c. Vertical (Z) +/- One Standard Deviation

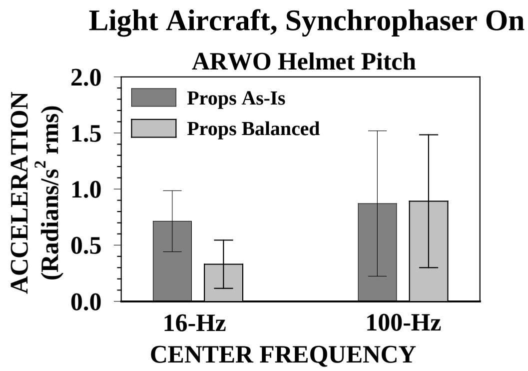


Figure C-9. Mean ARWO Helmet Pitch 16-Hz and 100-Hz One-Third Octave Band Accelerations +/- One Standard Deviation

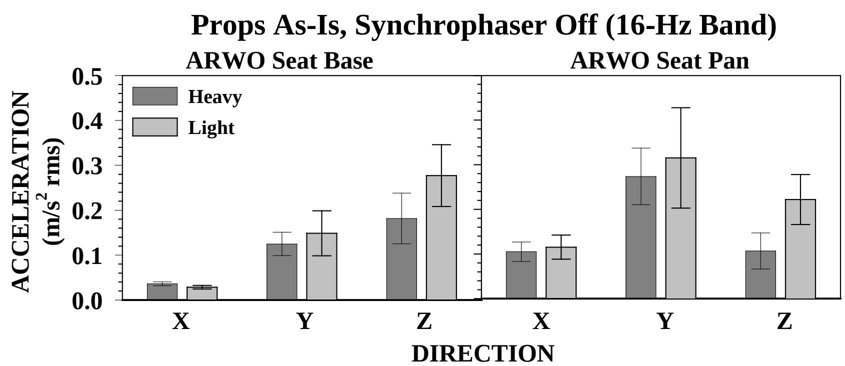


Figure C-10. Comparison of Heavy vs Light Aircraft, Mean 16-Hz One-Third Octave Band Accelerations +/- One Standard Deviation

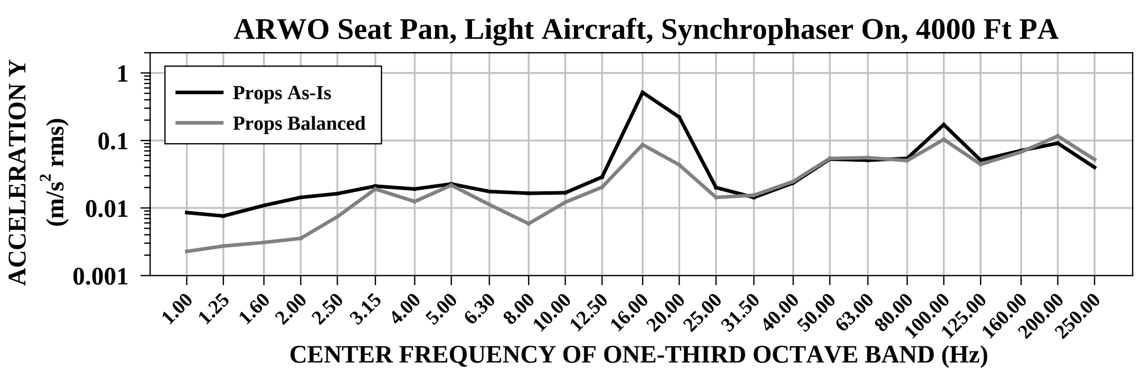


Figure C-11. Frequency Response Effect of Dynamically Balancing the Propellers. Lateral (Y) seat pan accelerations are shown.

Side Seat Pan, Light Aircraft, Props Balanced, Synchrophaser On, 24000 Ft PA

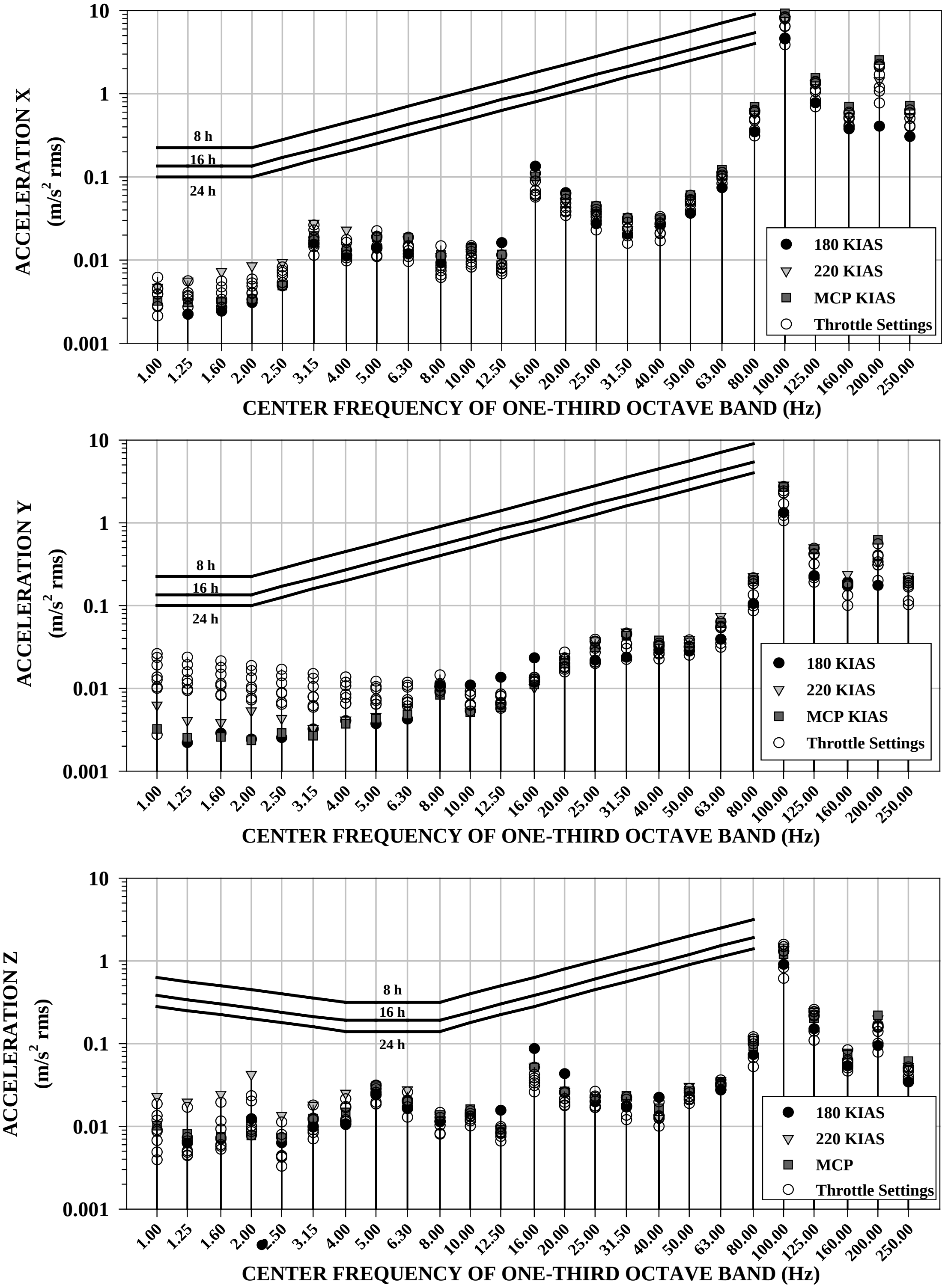


Figure C-12. C-130J (Slick) Left Side (Port) Passenger Fore-and-Aft (X), Lateral (Y), and Vertical (Z) One-Third Octave Band Accelerations

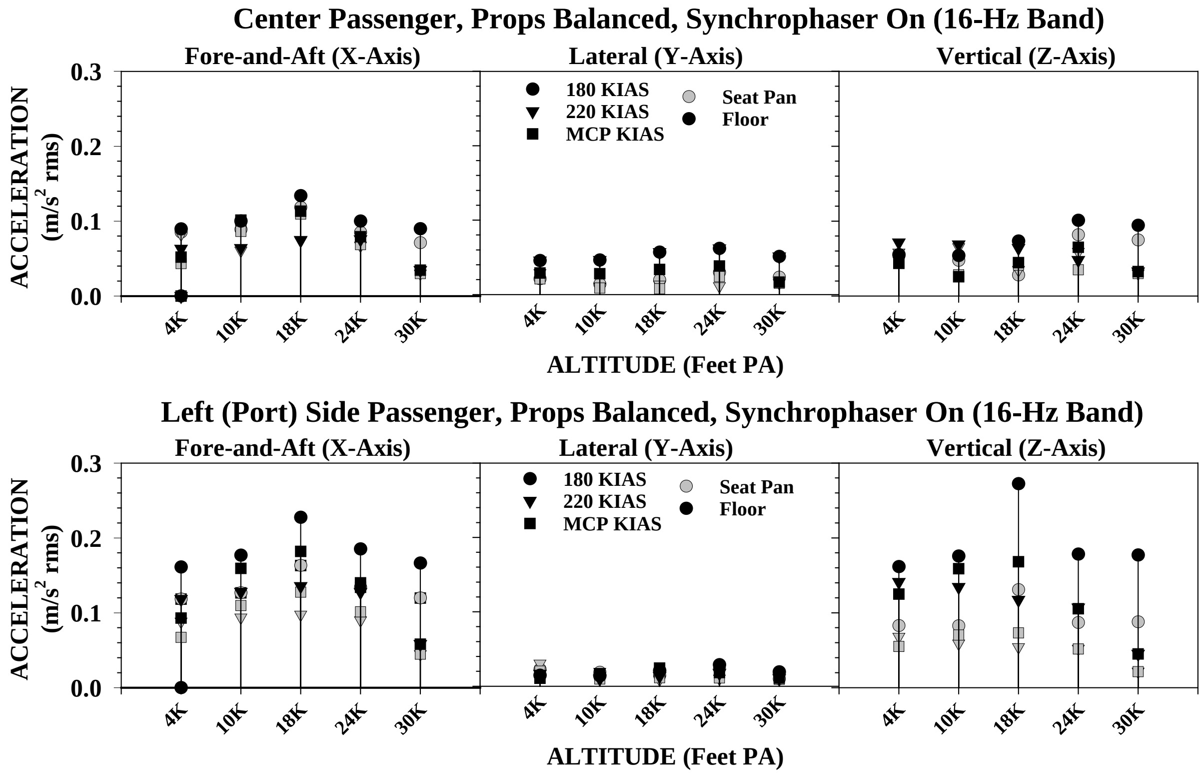


Figure C-13. C-130J (Slick) Center and Side Passenger 16-Hz One-Third Octave Band Accelerations

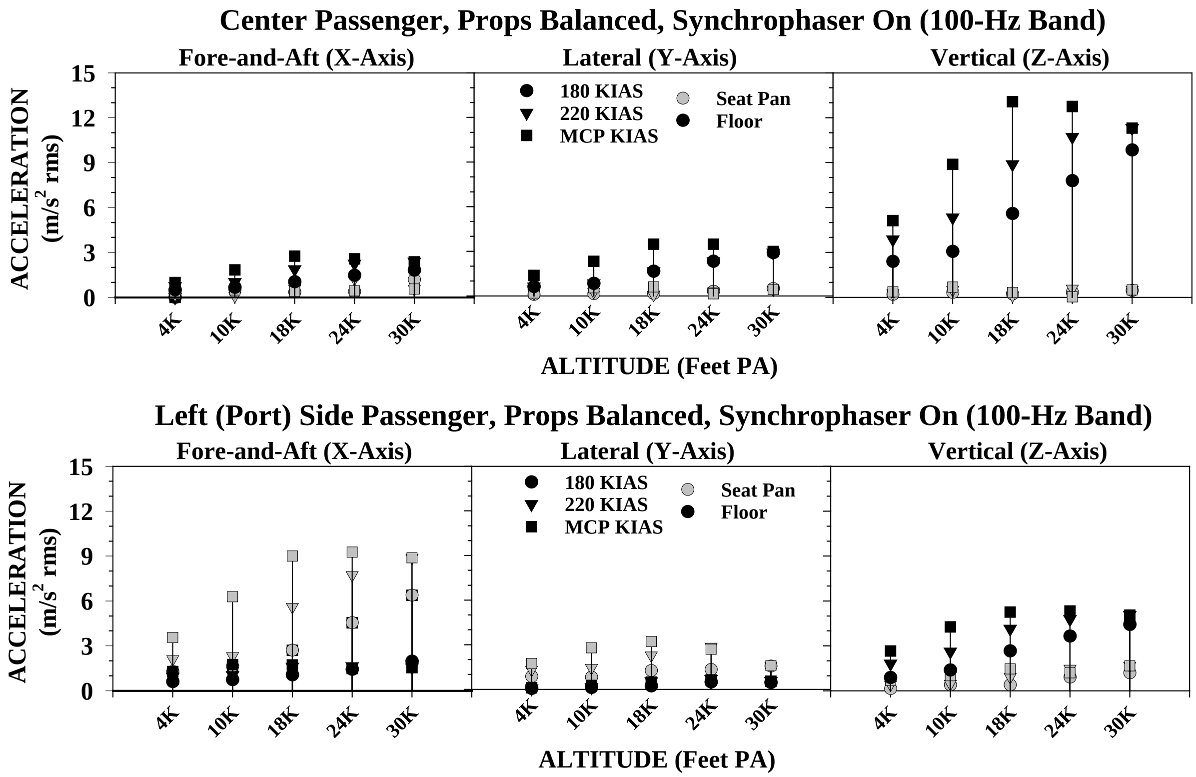


Figure C-14. C-130J (Slick) Center and Side Passenger 100-Hz One-Third Octave Band Accelerations

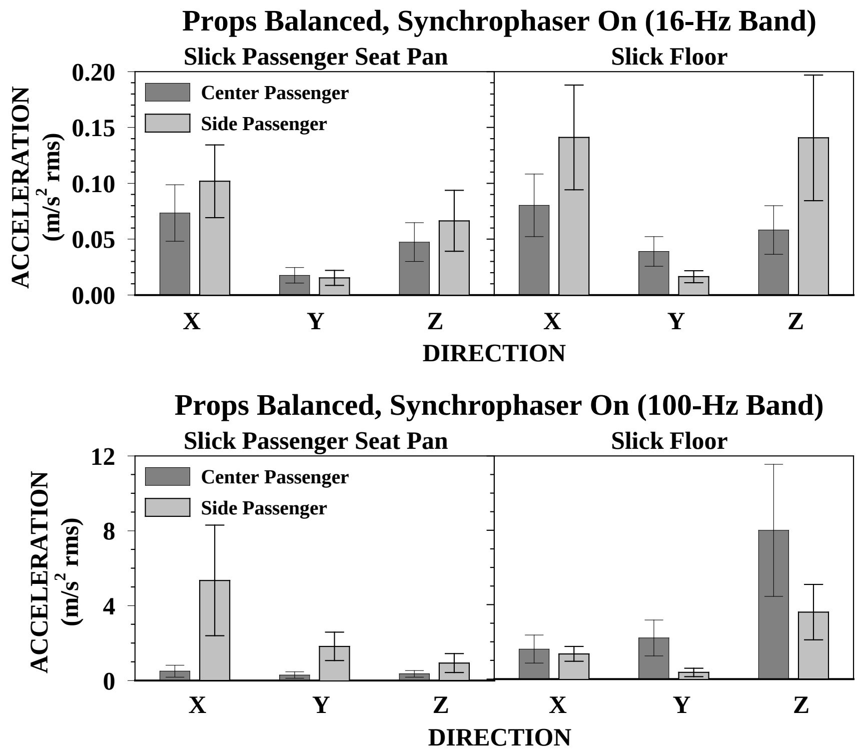


Figure C-15. C-130J (Slick) Center and Side Passenger Mean 16- and 100-Hz One-Third Octave Band Accelerations +/- One Standard Deviation

Copilot Seat Pan, Light Aircraft, Props Balanced, Synchrophaser On, 24000 Ft PA

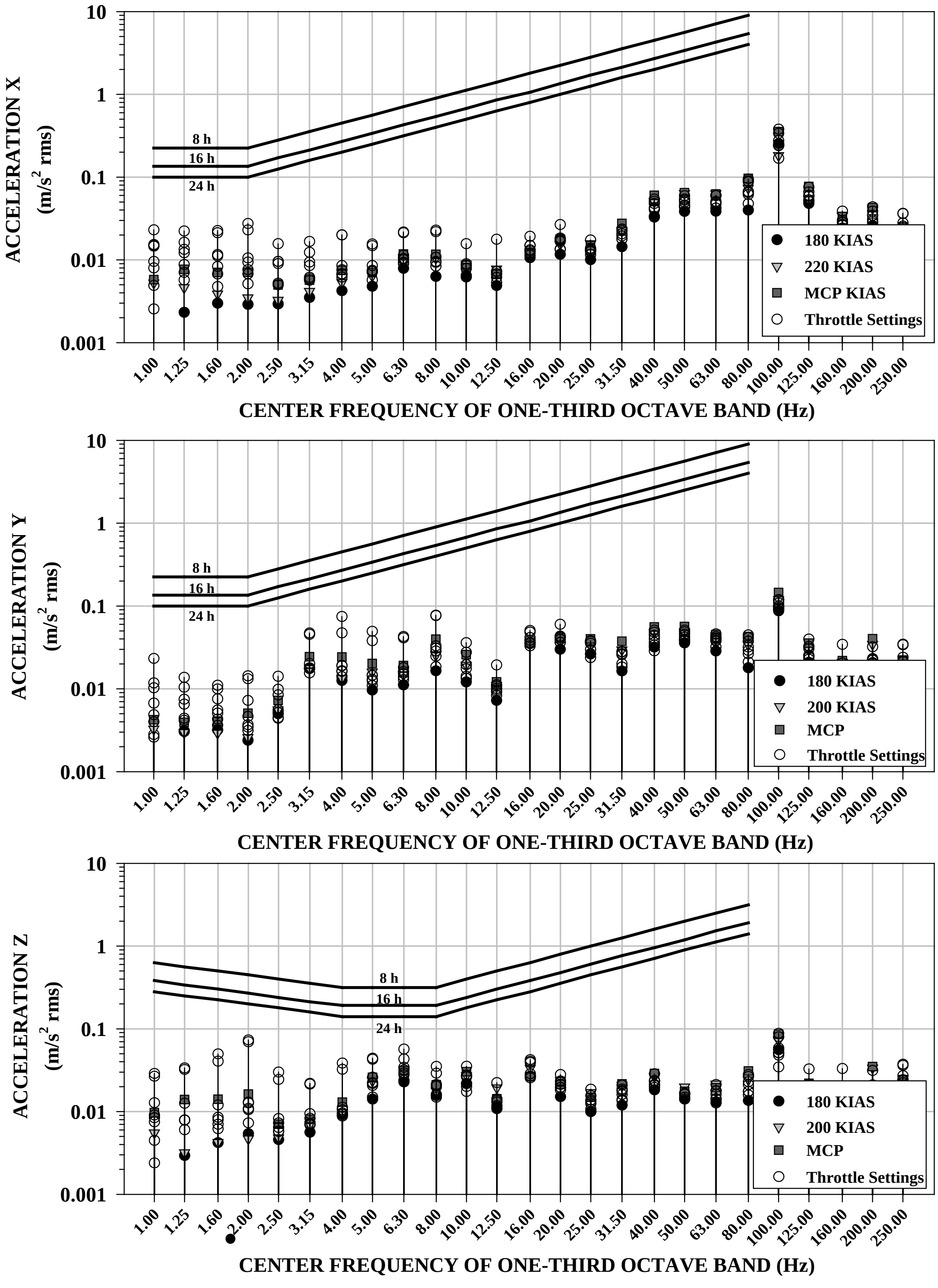


Figure C-16. Copilot Seat Pan Fore-and-Aft (X), Lateral (Y), and Vertical (Z) One-Third Octave Band Accelerations

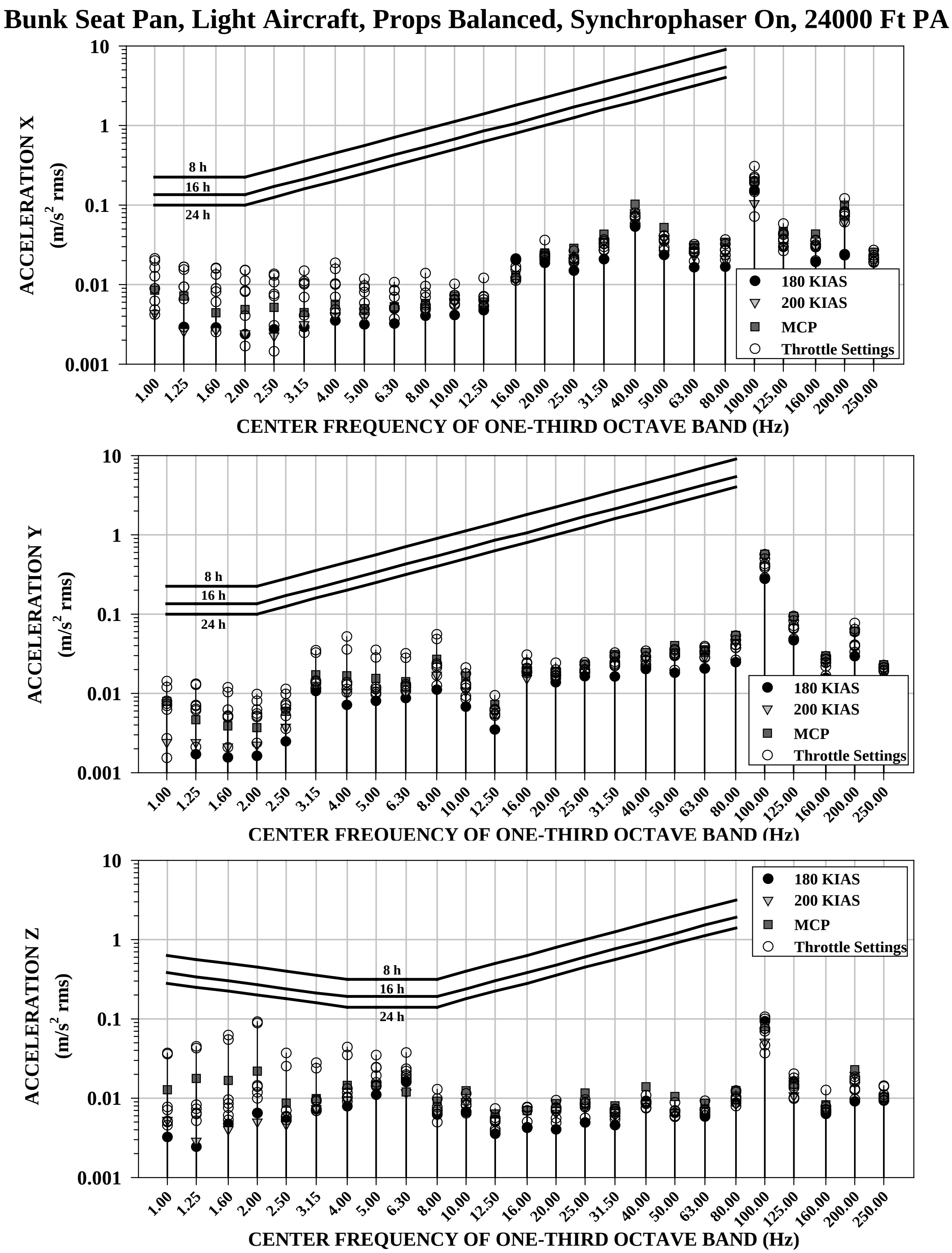


Figure C-17. Lower Bunk Seat Pan Fore-and-Aft (X), Lateral (Y), and Vertical (Z) One-Third Octave Band Accelerations

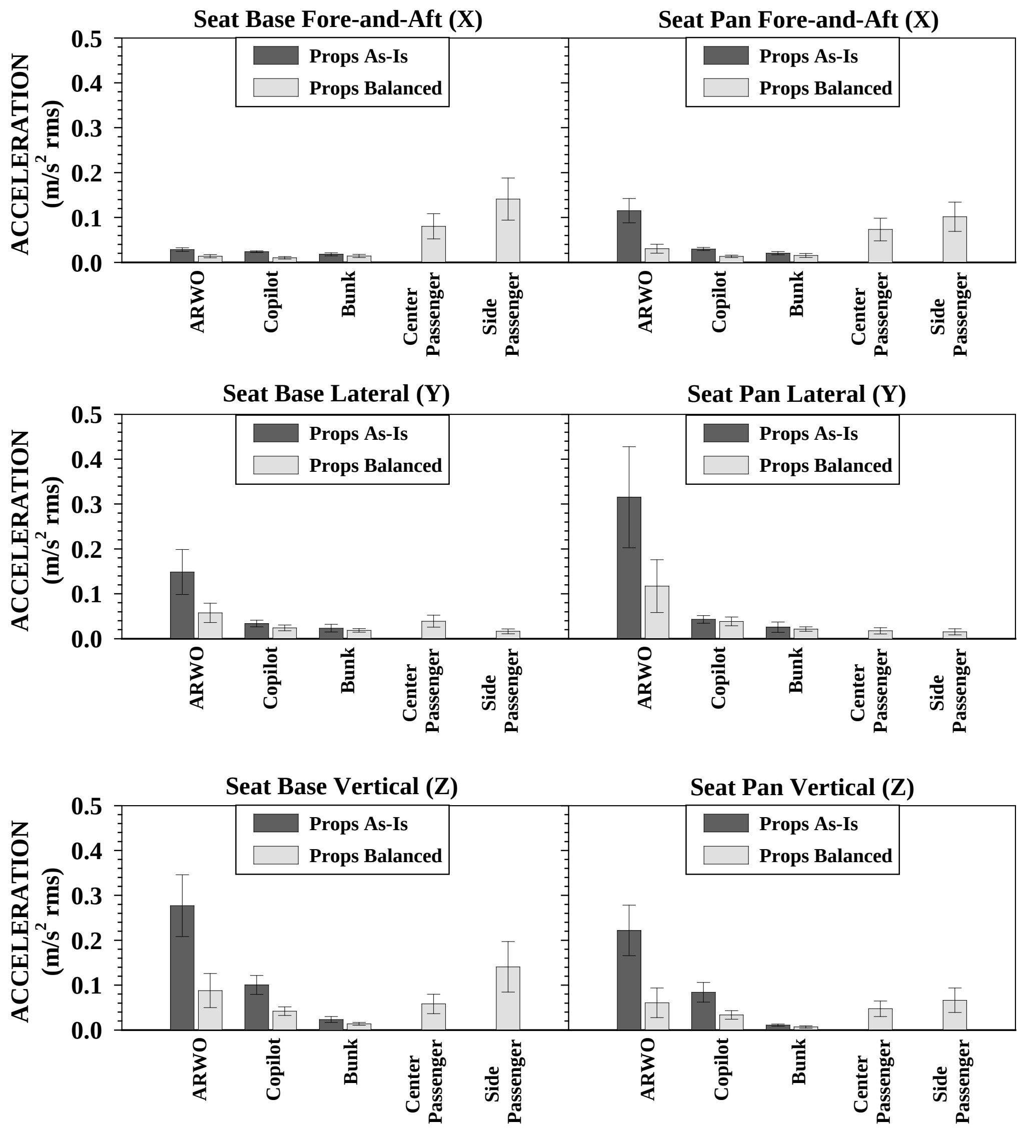


Figure C-18. WC-130J and C-130J Mean Seat 16-Hz One-Third Octave Band Accelerations +/- One Standard Deviation

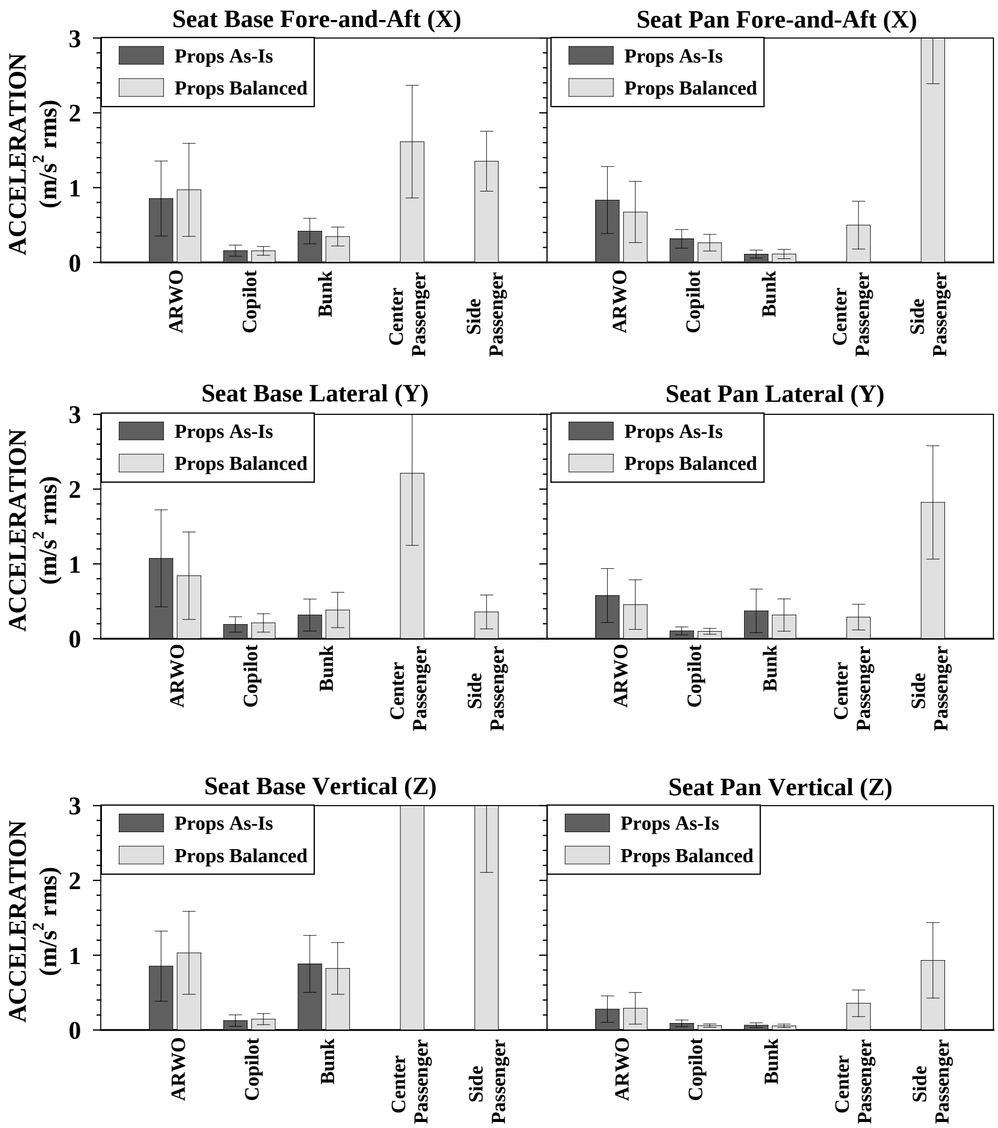


Figure C-19. WC-130J and C-130J Mean Seat 100-Hz One-Third Octave Band Accelerations +/- One Standard Deviation

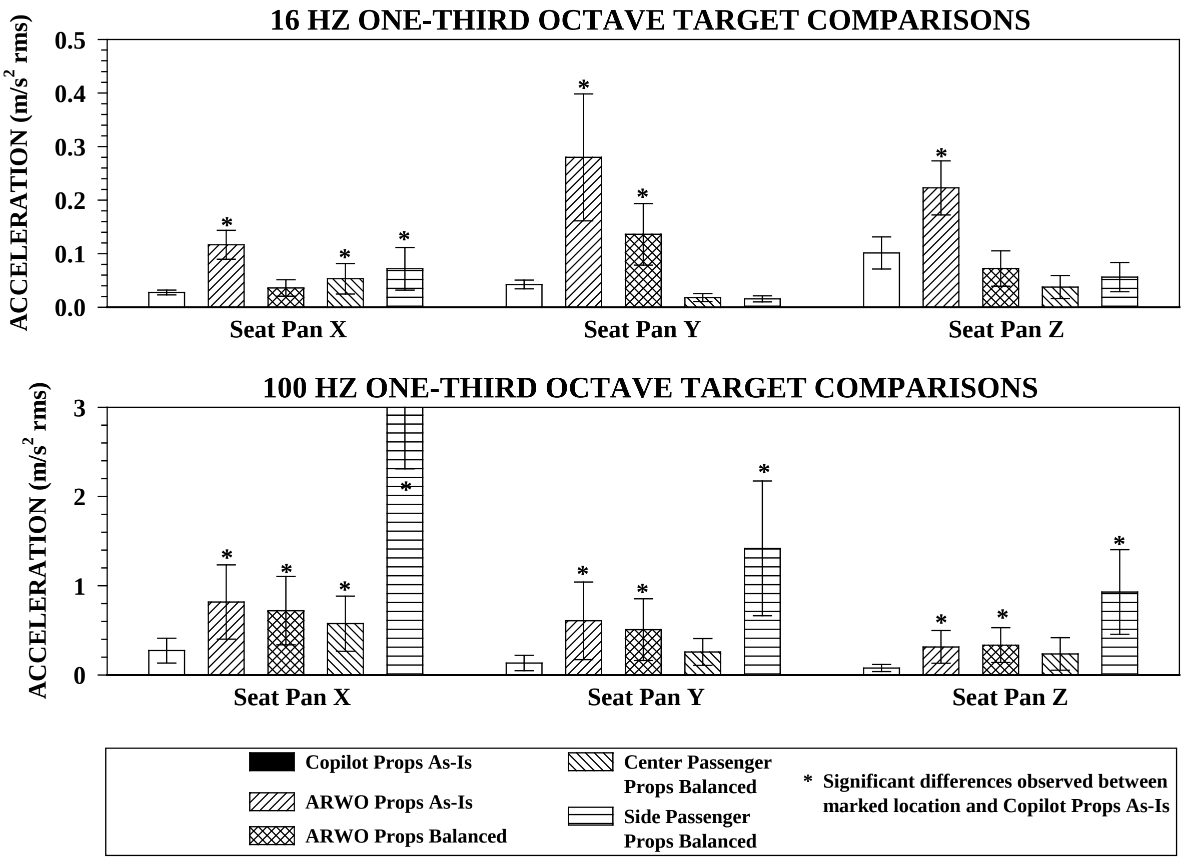


Figure C-20. 16-Hz and 100-Hz Frequency Band Target Acceleration Comparisons

DEPARTMENT OF THE AIR FORCE
AIR FORCE RESEARCH LABORATORY
WRIGHT-PATTERSON AIR FORCE BASE OHIO 45433-7008

17 April 12

MEMORANDUM FOR DTIC-OQ
ATTN: LARRY DOWNING
8725 JOHN J. KINGMAN ROAD
FORT BELVOIR, VA 22060-6218

FROM: 711 HPW/OMCA (STINFO)
2947 Fifth Street
Wright-Patterson AFB, OH 45433-7913

SUBJECT: Request to Change the Distribution Statement on a Technical Report

This memo documents the requirement for DTIC to change the distribution statement on the following technical report from distribution statement B to A. Approved for Public Release; distribution is unlimited.

AD Number: ADB275807
Publication number: AFRL-HE-WP-TR-2002-0005
Title: WC/C-130J Human Vibration Investigation

Reason for request: The information and representative data contained in this document are valuable resources for government, industrial, and academic institutions involved in the upgrade of subject equipment/aircraft, improvement of human interfaces (such as seating systems and helmet systems) to mitigate deleterious effects of equipment vibration on health and performance, equipment simulator development/enhancement, modeling of human response to equipment vibration, and the development/improvement of equipment design and exposure standards.

Donald Denio

DONALD DENIO
STINFO Officer
711th Human Performance Wing